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United States Department of Agriculture

Soil Conservation Service

St. Paul, Minnesota

LOOSE RIPRAP PROTECTION

Minnesota Technical Release 3
July 1989

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FOREWORD

The Soil Conservation Service in Minnesota is pleased to present this revised copy of Minnesota Technical Release #3, "Loose Riprap Protection". The document was revised to add background information, examples, and a glossary and to expand the bibliography. The changes in the design procedure are those that remove references to allowable velocity procedures and replace them with tractive stress evaluations.

This technical release is not meant to be used for the design of rock chutes, nor lined channels steeper than 5-6%. New research data from Colorado State University is being reviewed by National Headquarters for development of new riprap design procedures. Some of the research done is mentioned in this document but no specific design recommendations are given.

This document is also not meant for the design of side inlet channels. These tend to be sites with smaller drainage areas and steeper slopes that can tolerate a higher level of risk than in a channel lining situation. The user is referred to Design Note 22, Technical Release #59 and other documents for design of these structures.

March 29, 1989

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"LOOSE RIPRAP PROTECTION"

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CHAPTER 1. INTRODUCTION

This technical release was originally prepared in 1977 under the direction of Wendell L. Scheib. Additional research in this area, as well as added experience with field installations, led the Soil Conservation Service in Minnesota to release this revised document in 1989. This document does not address riprap used for lakeshore protection. That topic is addressed in Minnesota Technical Release No. 2, "Slope Protection for Dams and Lakeshores".

A. Failure Mechanisms

Prior to designing a bank stabilization measure, it is well to be aware of the common erosion mechanisms and riprap failure modes, and the causes or driving forces behind bank erosion processes. Many causes of bank erosion and riprap failure have been identified. Some of the more common include abrasion, debris flows, water flow, eddy action, flow acceleration, unsteady flow, freeze/thaw, human actions on the bank, ice, precipitation, waves, toe erosion, and subsurface flows. Most often a combination of mechanisms causes bank and riprap failure. The actual cause may be difficult to determine. Jim Blodgett (reference 13) has identified four classic riprap failure modes.

Particle Erosion
Translational Slide
Modified Slump
Slump

Particle erosion is a common erosion mechanism. Particle erosion results when the tractive force exerted by the flowing water exceeds the bank materials' ability to resist movement. In addition, if displaced stones are not transported from the eroded area, a mound of displaced rock will develop on the channel bed. This mound has been observed to cause flow concentration along the bank, resulting in further bank erosion.

Particle erosion can be initiated by abrasion, impingement of flowing water, eddy action/reverse flow, local flow acceleration, freeze/thaw action, ice or toe erosion. Figure 1-1 illustrates riprap failure by particle erosion. Probable causes of particle erosion include:

* Stone size not large enough.
* Individual stones removed by impact or abrasion.
* Side slope of the bank so steep that the angle of repose of the riprap material is easily exceeded.
* Gradation of riprap too uniform.

A translational slide is a failure of riprap caused by the downslope movement of a mass of stones, with the fault line on a horizontal plane. The initial phases of a translational slide are indicated by cracks in the upper part of the riprap bank that extends parallel to the channel. As the slide progresses, the lower part of riprap separates from the upper part,

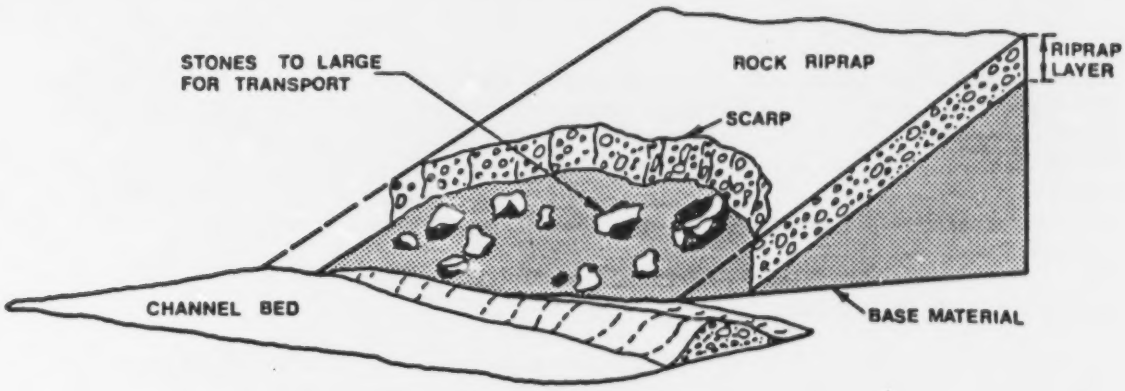


Figure 1-1. Particle Erosion Failure (adapted from reference 13)

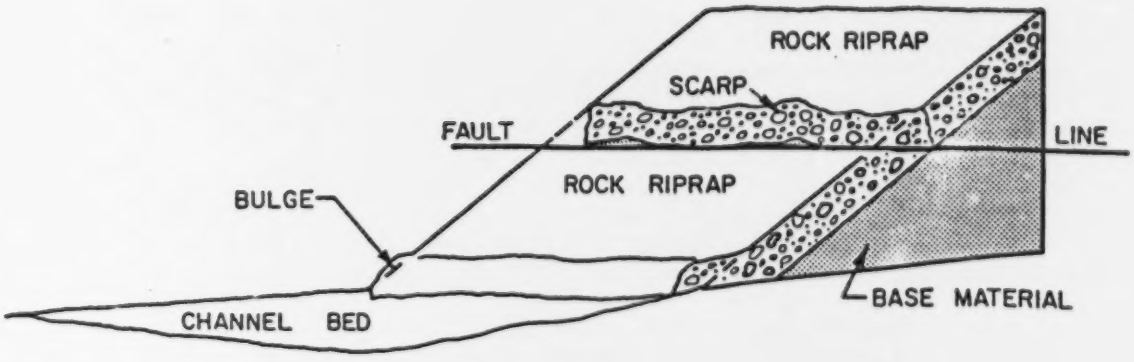


Figure 1-2. Translational Slide Failure (adapted from reference 13)

and moves downslope as a homogeneous body. A resulting bulge may appear at the base of the bank if the channel bed is not scoured.

Translational slides are usually initiated when the channel bed scours and undermines the toe of the riprap blanket. This could be caused by particle erosion of the toe material, or some other mechanism which causes displacement of toe material. Any other mechanism which would cause the shear resistance along the interface between the riprap blanket and base material to be reduced to less than the gravitational force could also cause a translational slide. It has been suggested that the presence of a filter blanket may provide a potential failure plane for translational slides (reference 13). Figure 1-2 illustrates a typical translational slide. Probable causes of translational slides are as follows:

* Bank side slope too steep.
* Presence of excess hydrostatic (pore) pressure.
* Loss of foundation support at the toe of the riprap blanket caused by erosion of the lower part of the riprap blanket (reference 13).

The failure of riprap referred to as modified slump is the mass movement of material along an internal slip surface within the riprap blanket. The underlying material supporting the riprap does not fail. This type of failure is similar in many respects to the translational slide, but the geometry of the damaged riprap is similar in shape to initial stages of failure caused by particle erosion. Figure 1-3 illustrates a modified slump failure. Probable causes of modified slump are:

* Bank side slope is so steep that the riprap is resting very near the angle of repose, and any imbalance or movement of individual stones creates a situation of instability for other stones in the blanket.

* Material critical to the support of upslope riprap is dislodged by settlement of the submerged riprap, impact, abrasion, particle erosion, or some other cause. (reference 13)

Slump is a rotational-gravitational movement of material along a surface of rupture that has a concave upward curve. The cause of slump failures is related to shear failure of the underlying base material that supports the riprap revetment. The primary feature of a slump failure is the localized displacement of base material along a slip surface, which is usually caused by excess pore pressure that reduces friction along a fault line in the base material. Figure 1-4 illustrates a slump failure. Probable causes of slump failure are:

* Nonhomogeneous base material with layers of impermeable material that act as a fault line when subject to excess pore pressure.

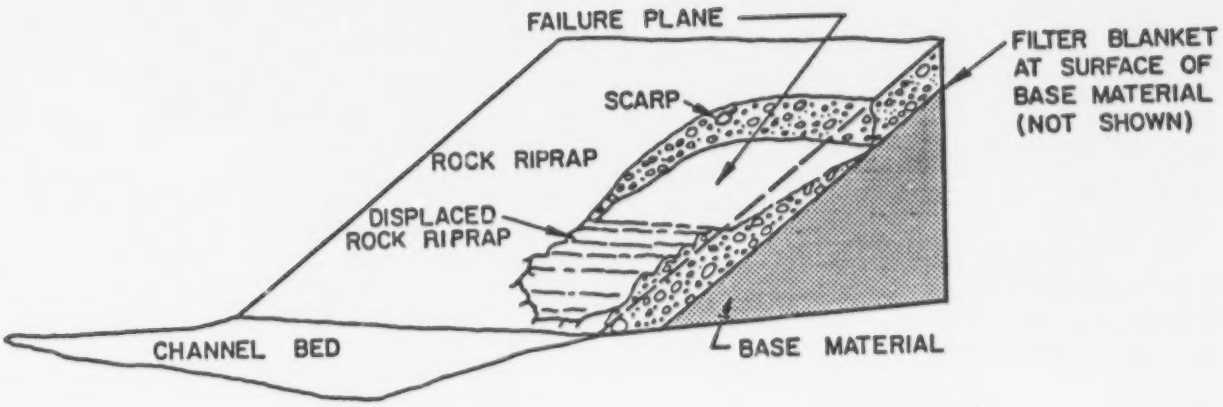


Figure 1-3. Modified Slump Failure (adapted from Reference 13)

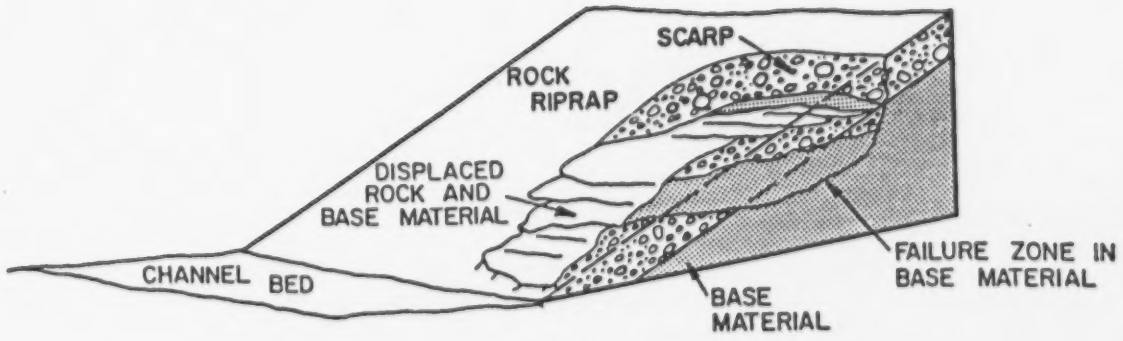


Figure 1-4. Slump Failure (adapted from reference 13)

* Side slope too steep, and gravitational forces exceed the inertia forces of the riprap and base material along a friction plane. (reference 13)

Additional details and examples explaining these erosion mechanisms or failure modes are available in reference 13. The riprap design guidelines presented in this circular apply to particle erosion only. Analysis procedures for other bank failure mechanisms are presented in reference 13.

B. Types of Riprap

Riprap is widely understood to mean a flexible protective layer that absorbs energy, and remains in place with no movement relative to the bank or members. Riprap is frequently rock or concrete members of varying shapes.

Rock riprap is the most widely used and considered the most desirable type of revetment in the United States. It is compatible with most environmental settings. The term "riprap" is often used to refer to rock riprap. For purposes of description, rock riprap is further subdivided by placement method into placed riprap, hand-placed riprap, and plated riprap.

Placed riprap is graded stone put on a prepared slope in such a manner that segregation will not take place. Placed riprap forms a layer of loose stone; individual stones can independently adjust to shifts in or movement of the base material. The placement of riprap should be done by mechanized means such as a crane and skip, dragline, or some form of bucket. End dumping from trucks causes segregation of the rock by size, reducing its stability, and therefore, should not be used as a means of placement. The effectiveness of placed riprap has been well established where it is properly installed, of adequate size, and suitable size gradation. Advantages associated with the use of placed rock riprap include:

* The riprap blanket is flexible and not impaired or weakened by minor movement of the bank caused by settlement or other minor adjustments.

* Local damage or loss can be repaired by placement of more rock.

* Construction is not complicated.

* When exposed to fresh water, vegetation will often grow through the rocks, adding aesthetic and structural value to the bank material and restoring natural roughness.

* Riprap is recoverable and may be stockpiled for future use.

One drawback to the use of rock riprap revetments is that they are more sensitive to local economic factors than other bank protection schemes. For example, freight/haul costs can significantly affect the cost of these revetments.

Hand-placed riprap is stone laid carefully by hand or by derrick following a definite pattern, with the voids between the larger stones filled with smaller stones and the surface kept relatively even. The need for interlocking stone in a hand-placed revetment requires that the stone be relatively uniform in size and shape (square or rectangular). Advantages associated with the use of hand-placed riprap include:

* The even interlocking surface produce a neat appearance and reduces flow turbulence at the water-revetment interface.

* The support provided by the interlocking of individual stones permits the use of hand-placed riprap revetments on steeper bank slopes than is possible with the same size loose stone riprap.

* With hand-placed riprap, the blanket thickness may be able to be reduced by 6 to 12 inches less than a loose riprap blanket, resulting in the use of less stone.

Disadvantages associated with hand-placed riprap include:

* Installation is very labor-intensive, resulting in high costs.

* The interlocking of individual rocks in hand-placed revetments results in a less flexible revetment; as mentioned above, a small shift in the base material of the bank can cause failure of large segments of the revetment.

* By their nature, hand-placed rock riprap revetments are more expensive to repair than are loose rock revetments.

Plated or keyed riprap is similar to hand-placed riprap in appearance and behavior, but different in placement method. Plated riprap is placed on the bank with a skip and then tamped into place using a steel plate, thus forming a regular, well-organized surface. Experience indicates that during the plating operations, the larger stones are fractured, producing smaller rock sizes to fill the voids in the riprap blanket.

Advantages and disadvantages associated with the use of plated riprap are similar to those listed above for hand-placed riprap. As with hand-placed riprap, riprap plating permits the use of steeper bank angles, and a reduction in riprap layer thickness (usually 6 to 12 inches less than loose riprap). Experience also indicates that riprap plating also permits the use of smaller stone sizes when compared with loose riprap. Like hand-placed riprap, riprap plating results in a more rigid riprap lining than loose riprap. This makes it susceptible to failure as a result of minor bank settlement. However, plated riprap installation is not as labor-intensive as that of hand-placed riprap.

Other types of revetment are discussed in reference 14. These include rubble, wire-enclosed rock (gabions), preformed blocks, grouted rock, and

paved lining. These may be used in combination with rock riprap and vegetation, as well as individually.

C. Design Discharge

The Soil Conservation Service's Standard 580 (Streambank and Lakeshore Protection) in the Technical Guide indicates the minimum level of protection. This may be increased due to proximity to a major road, high local damage potential, requirements of an upstream reservoir, or for other reasons. The designer should be aware that in some instances, a lower discharge may produce hydraulically worse conditions with respect to riprap stability. It is suggested that several discharge levels be evaluated to ensure that the design is adequate for all discharge conditions up to that selected as the overall design discharge. The Engineering Field Manual, Minnesota Hydrology Guide, and other SCS documents may prove helpful.

D. Flow Types

Open channel flow can be classified from three points of reference.

* Uniform, gradually varying, or rapidly varying flow
* Steady or unsteady flow
* Subcritical or supercritical flow

These flow states, and procedures for identifying them are covered in most open channel flow texts. Design relationships presented in this manual are based on the assumption of uniform, steady, subcritical flow. These relationships are also valid for gradually varying flow conditions. The individual hydraulic relationships presented are not in themselves applicable to rapidly varying, unsteady or supercritical flow conditions.

Rapidly varying, unsteady flow conditions are common in areas of flow expansion, flow contraction and reverse flow. These conditions are common at and immediately downstream of bridge crossings. Supercritical or near supercritical flow conditions are common at bridge constrictions and on steep sloped channels.

It has been observed that fully developed supercritical flow rarely occurs in natural channels. However, steep channel flow, and flow through constrictions is often in a transitional flow state between subcritical and supercritical. Experimental work conducted by the U.S. Army Corps of Engineers indicates that this transition zone occurs between Froude numbers of 0.89 and 1.13. When flow conditions are within this range, an extremely unstable condition exists in which the inertia and gravity forces are unbalanced. This causes excessive wave action, hydraulic jumps, localized changes in water-surface slope, and extreme flow turbulence.

Non-uniform, unsteady, and near supercritical flow conditions create stresses on the channel boundary that are significantly different from those induced by uniform, steady, subcritical flow. These stresses are

difficult to assess quantitatively. The stability factor presented here provides a means of adjusting the final riprap design (which is based on relationships derived for steady, uniform, subcritical flow) for the uncertainties associated with these other flow conditions. The magnitude of the stability factor is based on the level of uncertainty inherent in the design flow conditions.

E. Flow in Channel Bends

Flow conditions in channel bends are complicated by the distortion of flow patterns in the vicinity of the bends. In long, relatively straight channels, the flow conditions are uniform, and symmetrical about the center line of the channel. However, in channel bends, the centrifugal forces and secondary currents lead to non-uniform and non-symmetrical flow conditions. Two aspects of flow in channel bends impact the design of riprap revetments. First, special consideration must be given to the increased velocities and shear stresses that are generated as a result of non-uniform flow in bends. In the design procedure given, this may be accomplished by using the maximum cross section depth in place of average hydraulic radius.

Superelevation of flow in channel bends is the second important consideration in the design of riprap revetments. Although the magnitude of superelevation is generally small when compared with the overall flow depth in the bend (usually less than one foot), it should be considered when establishing freeboard limits for bank protection measures on sharp bends. The magnitude of superelevation at a channel bend may be estimated for subcritical flow by equation (1-1) below.

$$z = c[(Va^2 w)/(g r_c)] \qquad (1\text{-}1)$$

where,

z = superelevation of water surface (feet)
c = coefficient that relates free vortex motion to velocity streamlines for unequal radius of curvature
Va = mean channel velocity (ft/sec)
w = water surface width at section (feet)
g = gravitational acceleration (ft/sec^2)
r_c = the mean radius of the channel centerline at the bend (feet)

The coefficient c has recently been evaluated (reference 13). The value was found to range between 0.5 and 3.0, with the average around 1.5. Channel gradient, bed and bank roughness, and irregularities along the bank all increase c. An appropriate value should be based on channel conditions.

The extent and distribution of the local boundary shear in a bend of a trapezoidal channel with equal bottom and side roughness was discussed by A. T. Ippen. Figure 1-5 shows the result of some of his work. Note that

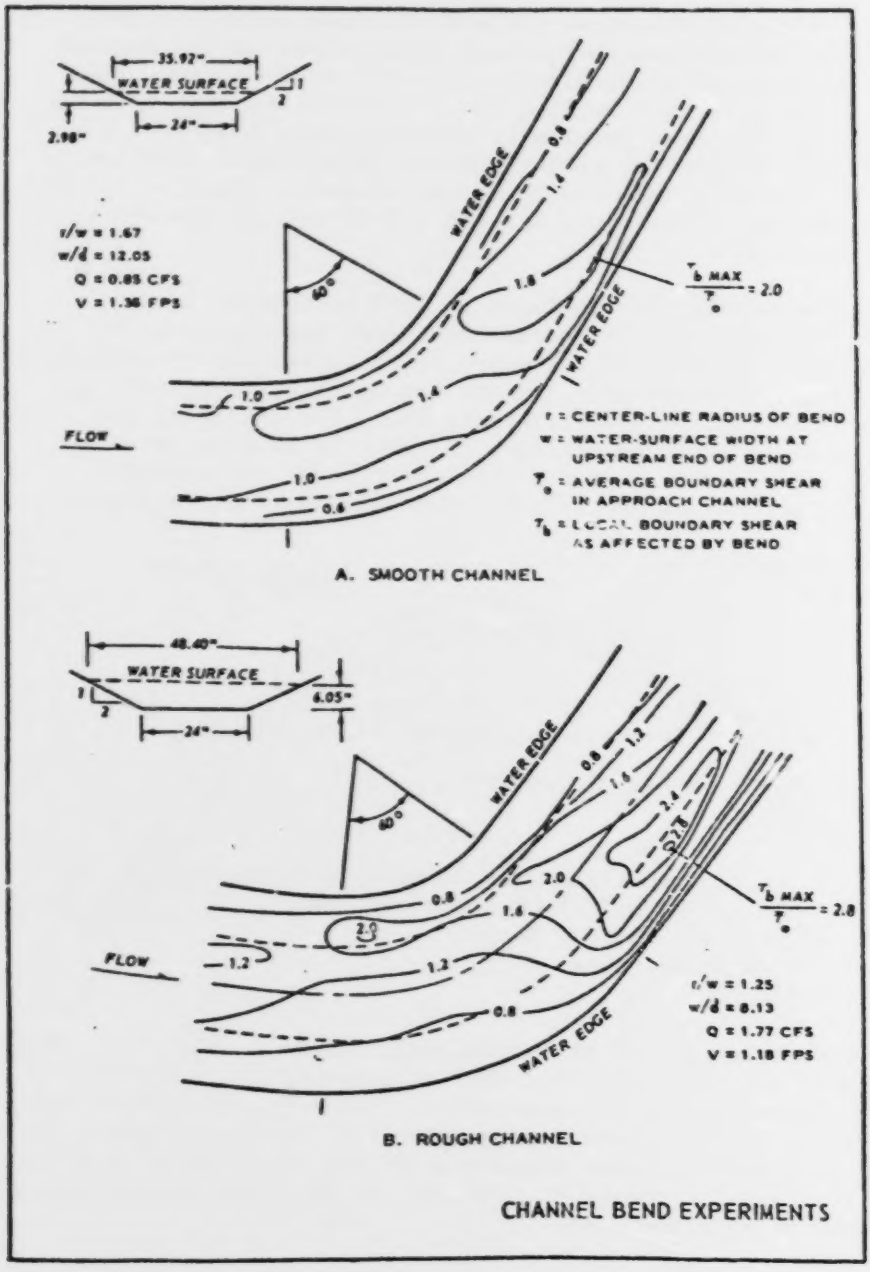

35.92"
WATER SURFACE
2.98"
24"
r/w = 1.67
w/d = 12.05
Q = 0.85 CFS
V = 1.36 FPS
60°
WATER EDGE
0.8
1.4
1.8
$\frac{\tau_{b\,MAX}}{\tau_o} = 2.0$
1.0
1.4
FLOW
1.0
0.8
r = CENTER-LINE RADIUS OF BEND
w = WATER-SURFACE WIDTH AT UPSTREAM END OF BEND
τ_o = AVERAGE BOUNDARY SHEAR IN APPROACH CHANNEL
τ_b = LOCAL BOUNDARY SHEAR AS AFFECTED BY BEND
A. SMOOTH CHANNEL
48.40"
WATER SURFACE
6.05"
24"
60°
WATER EDGE
0.8
1.3
1.6
2.4
2.8
2.0
$\frac{\tau_{b\,MAX}}{\tau_o} = 2.8$
1.6
2.0
FLOW
1.2
1.2
0.8
r/w = 1.25
w/d = 8.13
Q = 1.77 CFS
V = 1.18 FPS
WATER EDGE
B. ROUGH CHANNEL
CHANNEL BEND EXPERIMENTS

Figure 1-5.

upstream from the center of the curve the maximum shear occurs on the inside of the curve. Downstream the maximum shear occurs on the outside bank but downstream from the point of tangency (PT) of the curve. This points out that attention should be given to the area downstream from the curve also. Although the shear pattern is expected to be different for non-uniform sections, the general pattern should still exist. The top of the riprap must be raised by the amount, z, calculated in Equation 1-1 for the distances calculated in equations 1-2 and 1-3 as well as the curve itself. (See Figure 1-6)

The effect of a curve on the flow patterns of an open channel is not limited to within the curve itself. Flow turbulence and increases in tractive stress extend upstream of the point of curvature and downstream of the point of tangency. The upstream effects are believed to extend the distance expressed in equation 1-2 (reference 29). The extent of the downstream effects is believed to extend a distance Ld as determined by equation 1-3 from reference 29. Within these distances, the channel stability should be checked using the value for maximum tractive stress within the curve.

$$Lu = 0.4\ w \qquad (1\text{-}2)$$

where,

Lu = length upstream from the point of curvature to the end of the effect of the curve, feet

w = water surface width at design frequency, feet

$$Ld = (0.4635\ r^{0.1667} d)/n \qquad (1\text{-}3)$$

where,

Ld = length downstream from the point of tangency to the end of the effect of the curve, feet

r = hydraulic radius, feet

d = flow depth, feet

n = Manning's n

The rock riprap protection should be extended downstream to the point where the existing natural soil is stable for the increased tractive stress. This point can be determined using equation 1-4 (reference 29). Note that some of the terms are defined above for equation 1-3. It is necessary to check both the bottom and the sides downstream of the curve using equation 1-4. Therefore T_{all} and T_{st} should be computed for both the channel sides and bottom and used in equation 1-4.

$$Ld = (0.4635\ r^{0.1667} d)/n \times (Tc - T_{all})/(Tc - T_{st}) \qquad (1\text{-}4)$$

where,

Tc = tractive stress in the curve for the soil, psf

T_{all} = allowable tractive stress for the soil, psf

T_{st} = tractive stress in a straight reach for the soil, psf

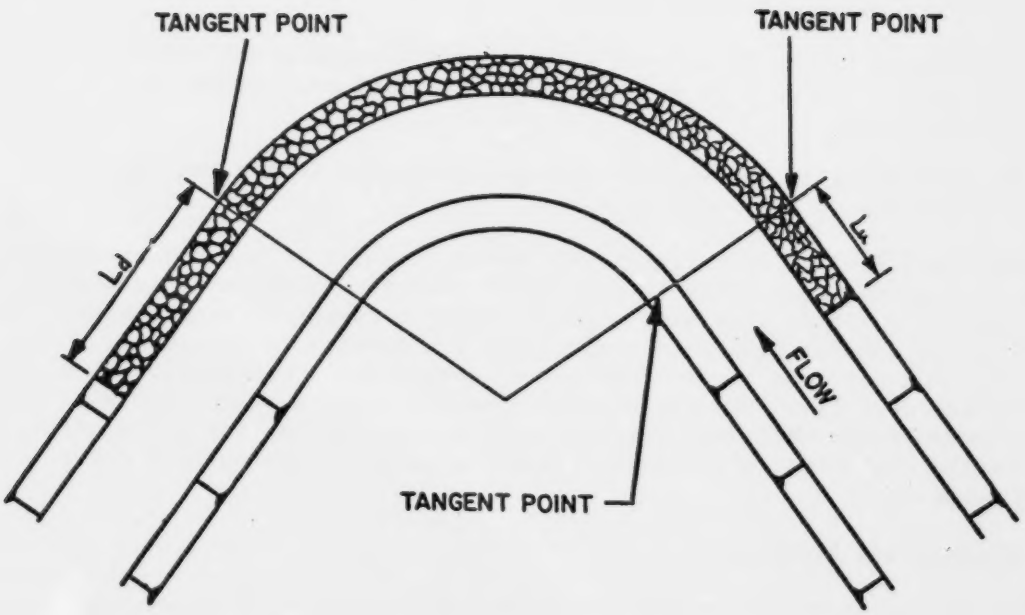


Figure 1-6. Extent of Riprap Protection on a Channel Bend

F. Geotextiles

The ASTM Subcommittee D-35 defines a geotextile as any permeable textile material used with foundation, soil, rock, earth or any geotechnical related material, that is an integral part of a man-made project, structure, or system. Woven geotextiles show a distinct pattern of threads criss-crossed, similar to fabric used to construct a garment. Non-woven geotextiles are a fused mass of filaments in a random pattern.

Geotextiles usually perform four primary functions:

1. Filtration is the ability of a geotextile to restrict solid particles from passing through it while allowing liquid to pass through. A good filter must perform both functions. That is, it must prevent the passage of fine particles, but not be so fine as to clog or plug up and not allow the passage of liquids.

2. Drainage is the ability of a geotextile to collect water and to convey it to a controlled outlet.

3. Separation is the ability of a geotextile to keep apart two soils that have a tendency to mix when they are squeezed together by applied loads.

4. Reinforcement is the ability of a geotextile to impart tensile strength when placed in a soil mass.

For many installations with riprap, non-woven geotextiles are preferred over woven geotextiles. This is especially true for slopes steeper than 3:1. Non-woven geotextiles have more friction to resist sliding. Also, the non-woven fabrics have more stretch and can conform to irregular surfaces and settlement better than woven geotextiles. Geotextiles should be selected carefully. Manufacturers frequently offer a selection, with each intended for a different purpose. SCS specifications for geotextiles indicate the tests that a geotextile should pass to be appropriate for a stated purpose.

G. Filters and Beddings

A filter is one or more transitional layers of gravel, small stone, or fabric placed between the underlying soil and the structure. The filter prevents migration of the fine soil particles through voids in the structure, distributes the weight of the armor units to provide more uniform settlement, and permits relief of hydrostatic pressures within the soils.

The proper design of granular and fabric filters is critical to the stability of riprap installations on channel banks. If openings in the filter are too large, excessive piping through the filter can cause erosion and failure of the bank material below the filter. On the other hand, if the openings in the filter are too small, the build-up of hydrostatic pressures behind the filter can cause a slip plane to form along the filter

resulting in massive translational slide failure. Figures 1-7 and 1-8 show proper and improper filter design.

H. Side Inlet Channels

This document is not intended to be used for the design of side inlet channels. These tend to be steep and short. They often have a different hazard or risk than a section of channel lining. The user is referred to Design Note #22 (reference 28) for the design of these structures. Technical Release #59 (reference #5) may be helpful also. A filter is required between the base soil and the riprap. The flow will try to go through the riprap and cause erosion of the base soil and will undermine the riprap.

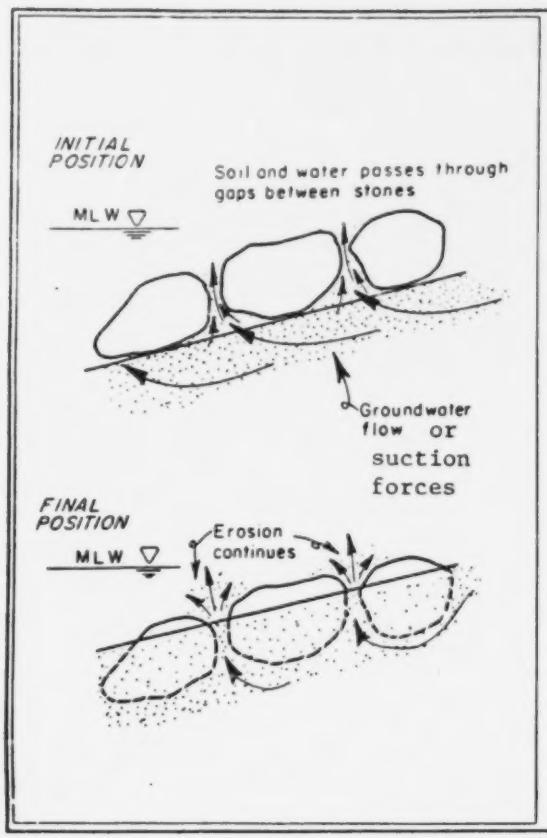


Figure 1-7
Inadequate or No Filtering

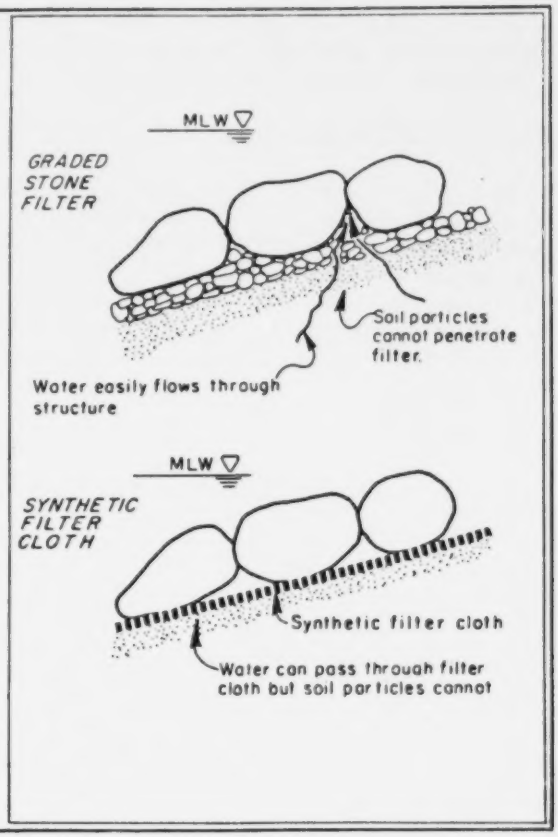


Figure 1-8
Proper Filter Design

CHAPTER 2. DESIGN GUIDELINES

Two methods or approaches have been used historically to evaluate a material's resistance to particle erosion. These methods are the permissible velocity approach and the permissible tractive force (shear stress) approach. Under the permissible velocity approach the channel is assumed stable if the computed mean velocity is lower than the maximum permissible velocity. The tractive force (boundary shear stress) approach focuses on stresses developed at the interface between flowing water and materials forming the channel boundary. Permissible velocity procedures were first developed in the 1920's. In the 1950's permissible tractive force procedures became recognized, based on research investigations conducted by the Bureau of Reclamation.

A. Estimating Relationships

More recently, Blodgett (references 12 & 13) has presented a tentative design relationship based on field data. This relationship is given in equation 2-1. It is also expressed in Figure 2-1.

$$D50 = 0.010\ Vmc^{2.44} \qquad (2\text{-}1)$$

where,

D50 = the median riprap size in feet

Vmc = the average velocity in the main channel, ft/sec

This equation is helpful for estimating the size of riprap needed. However, use of a design method based on tractive stress is still preferred for final design. The following information uses tractive stress design guidelines.

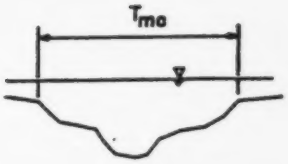
B. Design Relationships

The hydrodynamic force of water flowing in a channel is known as the tractive force. The basic premise underlying riprap design based on tractive force theory is that the flow-induced tractive force should not exceed the permissible or critical shear stress of the riprap. Assuming a specific gravity of 2.50, equation 2-2 can be used to determine D50 of the riprap by the tractive stress method (reference 14, page 30).

$$D50 = 14.2\ SF\ dmax\ Se/K1 \qquad (2\text{-}2)$$

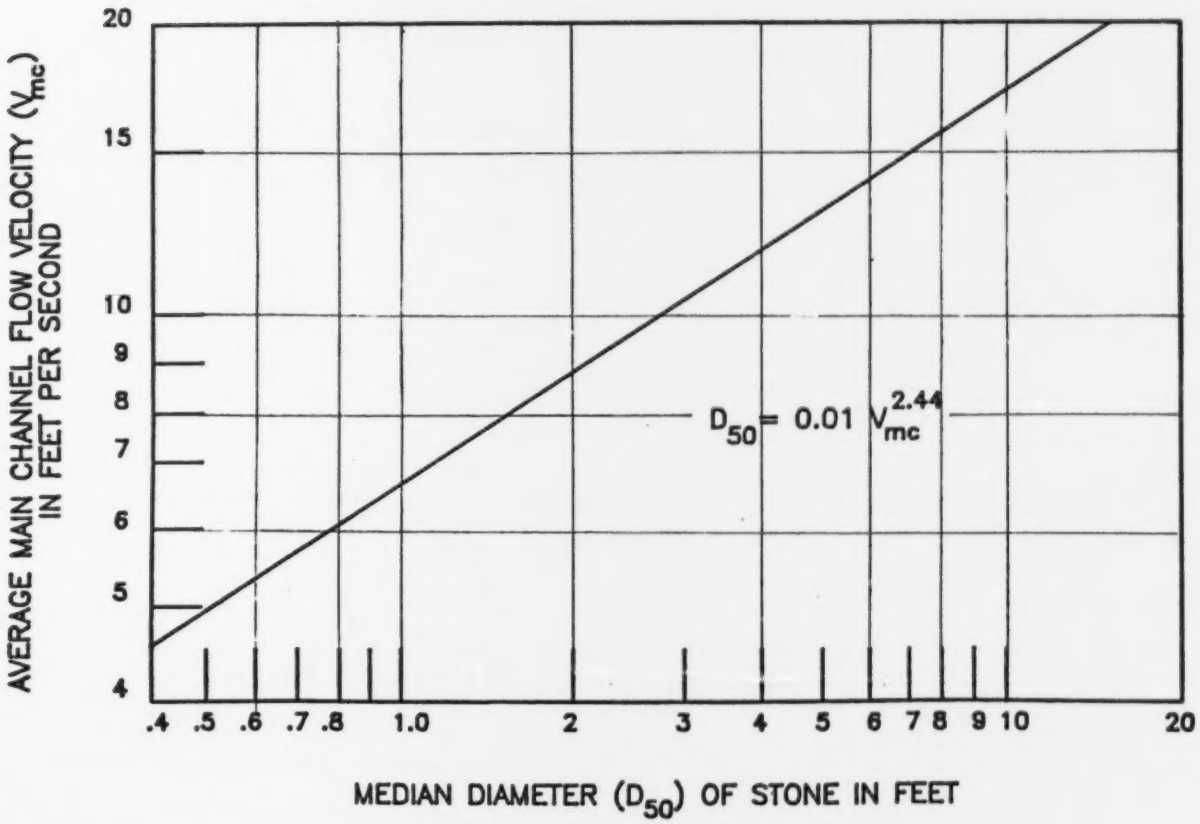
where,

SF = stability factor
dmax = maximum section depth, feet
Se = average energy grade line slope, ft/ft
D50 = median riprap size in feet
K1 = bank angle modification factor (see eq'n 2-3 or Fig. 2-4)



T_{mc} = MAIN CHANNEL TOPWIDTH
Q_{mc} = MAIN CHANNEL DISCHARGE
A_{mc} = MAIN CHANNEL FLOW AREA
V_{mc} = AVERAGE VELOCITY IN MAIN CHANNEL
D_{50} = MEDIAN RIPRAP SIZE

$$V_{mc} = \frac{Q_{mc}}{A_{mc}}$$



NOTE: USE THIS CHART FOR PRELIMINARY RIPRAP SIZING ONLY.

Figure 2-1. PRELIMINARY RIPRAP SIZE RELATIONSHIP from reference 13

$$K1 = [1-(\sin^2\phi/\sin^2\theta)]^{0.5} \qquad (2\text{-}3)$$

where,

ϕ = bank angle with horizontal, degrees

θ = riprap material angle of repose, degrees (see Fig. 2-3)

The stability factor, SF, in equation 2-2 is used to reflect the level of uncertainty in the hydraulic conditions at a particular site. Uniform or gradually varying flow is assumed. In many instances, these assumptions are violated or other uncertainties come to bear such as debris and/or ice impacts, or the cumulative effect of high shear stresses and forces from wind or boat generated waves. The stability factor is used to increase the design rock size when these conditions come to bear. The design rock size (D50) increases linearly with the stability factor. Table 2-1 presents guidelines for selection of an appropriate value for the stability factor. In uniform flow, the energy grade line slope, Se, is approximately equal to the water surface slope. It can be determined from computer backwater models such as WSP2.

Table 2-1 Criteria for Selection of Stability Factor

Condition	Stability Factor Range
Uniform flow: straight or mildly curving reach; little or no uncertainty in design	1.0 - 1.2
Gradually varying flow: moderate bend curvature; limited or minor impact from floating debris or ice	1.2 - 1.4
Sharp bend: Significant impact potential from floating debris or ice; significant wind/or boat generated waves. (1.0-2.0 ft); high flow turbulence	1.4 - 1.6
Rapidly varying flow (particularly due to rapid drawdown at flow constrictions): Significant uncertainty in design.	1.6 - 2.0

In some cases it is necessary to specify the design riprap size in terms of weight based on W50 (median riprap size by weight, lbs.). Figure 2-2 gives the conversion between weight and dimension for different shapes of stone in both tabular and equation form.

Figure 2-2. Stone Weight and Equivalent Stone Dimension Weights in Lbs.

Size	100% Angular	25% Round 75% Ang	50% Round 50% Ang.	75% Round 25% Ang	100% Round
3"	3	2	2	2	1
4"	6	5	5	4	3
6"	21	18	16	13	11
8"	49	43	37	32	26
9"	70	60	55	45	35
10"	95	85	75	60	50
12"	165	145	125	105	85
15"	320	285	245	210	170
18"	555	490	425	360	295
24"	1320	1165	1010	855	695
c*	0.036	0.0318	0.0275	0.0233	0.019

Eqn: $W = c^* G_s D^3$ $G_s = 2.65$

W = weight, lbs. G_s = specific gravity

D = dimension, inches

c*= constant, see above

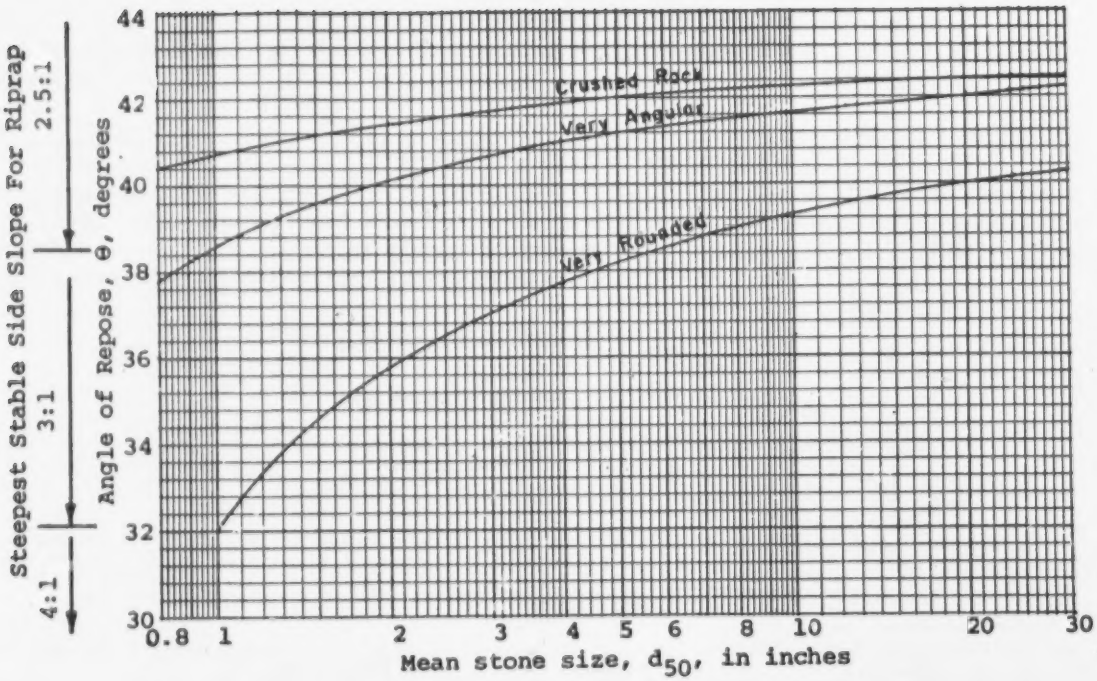
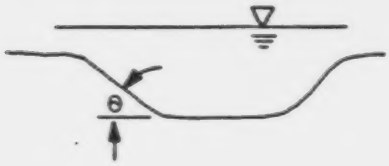
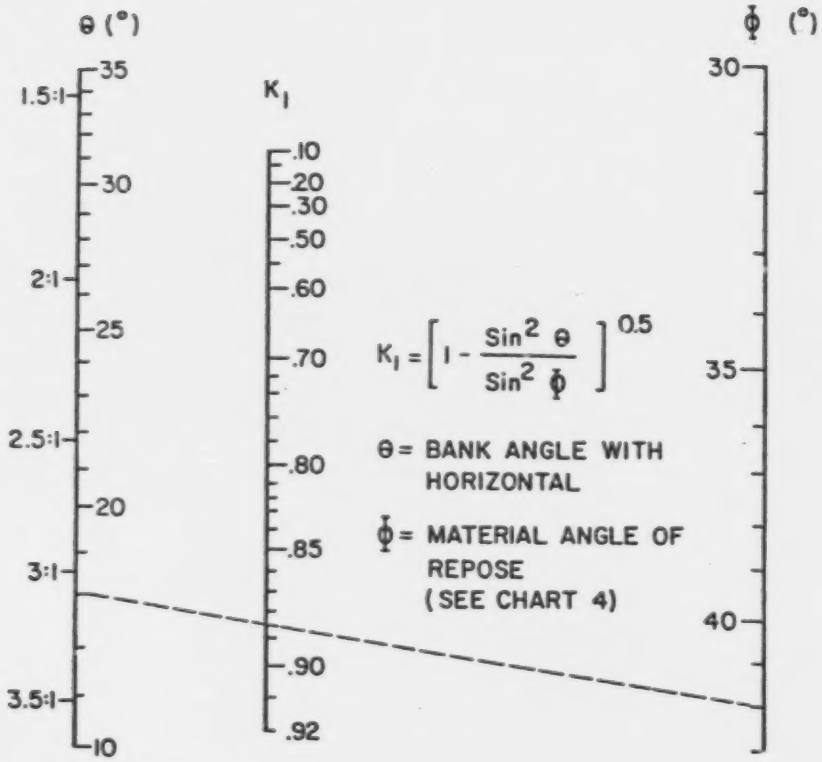


Figure 2-3. Optimum Riprap Side Slope for a Given Size Riprap





EXAMPLE

GIVEN:	FIND:	SOLUTION:
$\theta = 18°$	K_1	$\Phi = 42°$
VERY ANGULAR		$K_1 = 0.885$
$D_{50} = 1.5$ ft.		

Figure 2-4. BANK ANGLE CORRECTION FACTOR (K_1) NOMOGRAPH

C. Ice Damage

Ice can affect riprap linings in a number of ways. Moving surface ice can cause crushing and bending forces as well as large impact loadings. The tangential flow of ice along a riprap lined channel bank can also cause excessive shearing forces. Quantitative criteria for evaluating the impact ice has on channel protection schemes are unavailable. However, historic observations of ice flows in New England rivers indicate that riprap sized to resist design flow events will also resist ice forces (reference 15).

For design, ice forces should be evaluated on a case by case basis. In most instances, ice flows are not of sufficient magnitude to warrant detailed analysis. Where ice flows have historically caused problems, a stability factor of 1.2 to 1.5 should be used to increase design rock size. The selection of an appropriate stability factor to account for ice-generated erosive problems should be based on the designer's experience.

D. Rock Gradation

The gradation of stones in riprap revetment affects the riprap's resistance to erosion. The stone should be reasonably well graded throughout the riprap layer thickness. After a D50 has been determined for the location, the gradation should be stated using the guidelines in Table 2-2.

Table 2-2. Riprap Gradation Guidelines

Size of Stone	Percent of total weight smaller than the given size
1.5 to 2.0 x D50	100
1.3 to 1.8 x D50	85
1.0 to 1.5 x D50	50
0.3 to 0.5 x D50	15

Normally a gradation envelope is specified to allow for more flexibility in manufacturing the material to meet specified gradations. This may be specified in terms of length (inches or feet diameter) or weight (lbs. or tons). Chapter 7 provides helpful information for judging the weight of rock in the field and for checking the gradation with a sample in the field.

E. Layer Thickness

Research done at Colorado State University (reference #19) indicates that increasing rock layer thickness improves the riprap stability. The increase found in stability became smaller as the median rock size increased. The study examined only rock gradations where the median rock size was 6 inches or less.

All stones used should lie within the riprap blanket to provide the maximum resistance against erosion. Protruding stones can alter the flow net across the channel. Oversize stones, even in isolated spots, may cause riprap failure by precluding mutual support between individual stones, providing large voids that

expose filter and bedding materials, and creating excessive local turbulence that removes smaller stones. Small amounts of oversize stone should be removed individually and replaced with proper size stones. The following criteria apply to the riprap layer thickness.

1. The thickness should not be less than 1.25 times the diameter of the upper limit D100 (W100) stone.

2. The thickness should not be less than 12 inches for practical placement. For effective protection, the thickness should not be less than 9 inches.

3. The thickness determined by either 1 or 2 above should be increased by 50 percent in all sections when the riprap is placed underwater in water deeper than 3 feet to provide for uncertainties associated with this type of placement.

4. An increase in thickness of 6 to 12 inches, accompanied by an appropriate increase in stone sizes, should be provided where riprap revetment will be subject to attack by floating debris or ice or by waves from boat wakes or wind.

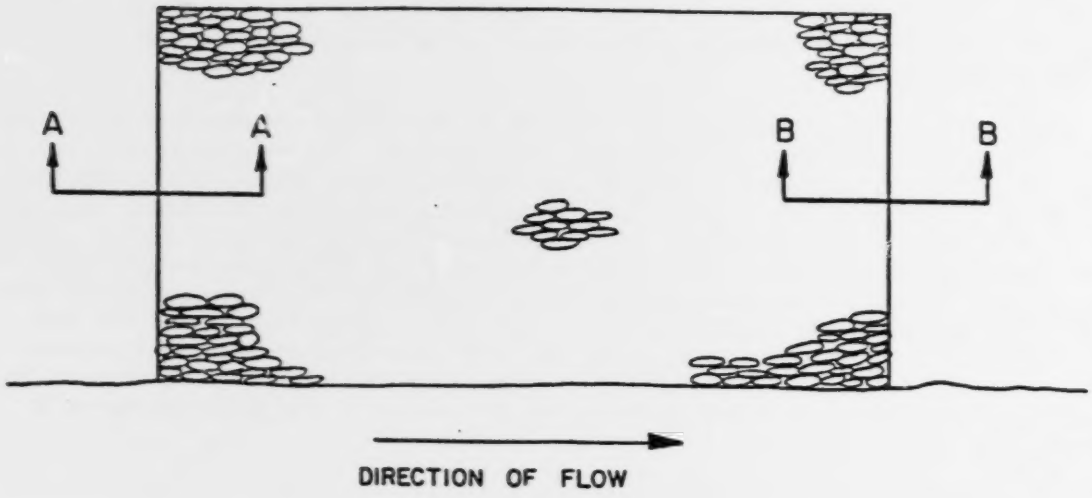
Experiences in Minnesota have shown that these thicknesses are adequate regardless of whether a granular filter or a geotextile is used with riprap.

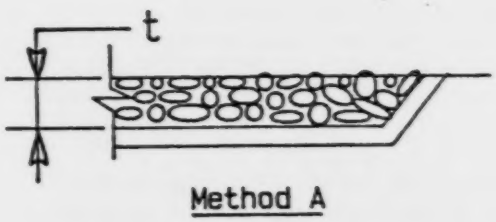
F. Material Quality. Riprap must be hard, dense and durable. It should be resistant to weathering, free from overburden, spoil, shale, and organic material. Rock or rubble that is laminated, fractured, porous, or otherwise physically weak is unacceptable as rock slope protection. The material specification for riprap should be referenced in construction documents.

G. Allowable Side Slopes. The stability of the riprap on the side slope of a channel is dependent on the angularity of the rock. The more angular the rock, the higher the angle of repose. This is evident in Figure 2-3. The riprap stability is related to the side slope, rock size, angularity of the rock, and the angle of repose. The maximum (steepest) slope for riprap is recommended to be 2:1 (that is, two feet horizontally for every foot of vertical height). For small areas, such as around existing culverts or transitions where slopes steeper than 2:1 cannot be avoided, slopes up to 1:1 can be tolerated, provided the riprap thickness and size are increased. Very angular rock must be used and carefully installed. The thickness shall be increased by 10% for 1.5:1 side slopes and by 20% for 1:1 side slopes. The minimum D50 that can be used on slopes steeper than 2:1 is 4 inches. This must be angular rock, not rounded.

H. Edge Treatment. The edges of riprap revetments are subject to additional forces by being adjacent to other materials. The top, toe and flanks require special treatment to prevent undermining.

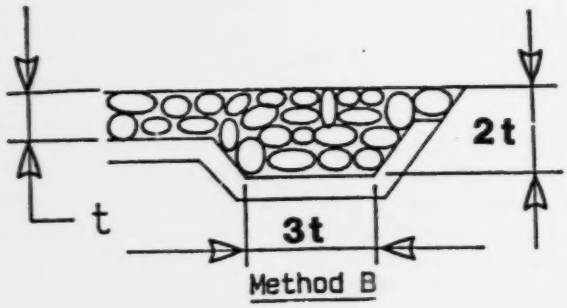
Flanks. The flanks of the revetment should be designed as illustrated in Figure 2-5. If the riprap ends at a bridge abutment or other secure point, special flank protection is not needed. If the riprap does not terminate at a stable





Notes:

1. Use Method B at section A-A (upstream edge).
2. Either Method A or Method B may be used at the downstream edge (section B-B).
3. t is the thickness of the riprap layer.



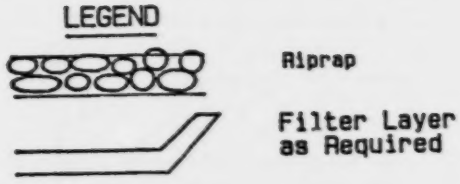


Figure 2-5. End Protection

point, the cross-section shown as Method B should be considered for the downstream edge as well.

Toe. Undermining of the revetment toe is one of the primary mechanisms of riprap failure. Figure 2-6 shows toe protection alternatives. It is prefereable to design the toe as illustrated in Figure 2-7 (Method B from Figure 2-6). The toe material is placed in a toe trench along the entire length of the riprap blanket. Where a toe trench cannot be dug, the riprap blanket may terminate in a thick, narrow stone toe at the level of the streambed (see the alternate design in Figure 2-7). Care must be taken during the placement of the stone to ensure that the toe material does not mound and form a low dike; a low dike along the toe could result in flow concentration along the revetment face which could stress the revetment to failure. In addition, care must be exercised to ensure that the channel's design capacity is not impaired by placement of too much riprap in a toe mound.

The size of the toe trench or alternate stone toe is controlled by the anticipated depth of scour along the revetment. As scour occurs (and in many cases it will) the stone in the toe will launch into the eroded area as illustrated in Figure 2-8. Observation of the performance of these types of rock toe designs indicates that the riprap will launch to a final slope of approximately 2:1. The volume of rock required for the toe must be equal to or exceed one and one-half times the volume of rock required to extend the riprap blanket (at its design thickness and on a slope of 2:1) to the anticipated depth of scour.

I. Bedding Selection Criteria. Riprap should be placed on a strong, stable, erosion-resistant base. Erosion of the base may occur from surface or seepage water flowing down the slope and from the surging action of waves or flowing water. Riprap reduces the growth of erosion controlling vegetation. Minor erosion that would be simple to repair on the surface will become more expensive and difficult to repair when it occurs beneath the riprap. Riprap needs a strong stable foundation to prevent shifting of the stone.

First consider if the base materials are adequate to bed the riprap. Coarse grained soil is needed with enough gravel of a large enough size to resist movement. Base soils that have a maximum of 20% fines and a minimum of 40% gravel do not need bedding. A soil with less gravel might be adequate where some near surface erosion of the fines and sands could be allowed to build a gravel surface layer. Where the natural materials do not have the necessary characteristics a bedding material must be used.

The layer immediately below the riprap should meet the bedding criteria given as equations 2-5a and 2-5b. If a filter is needed, the bedding must meet the filter criteria (equations 2-6 through 2-8) or else filter layers are needed below the bedding.

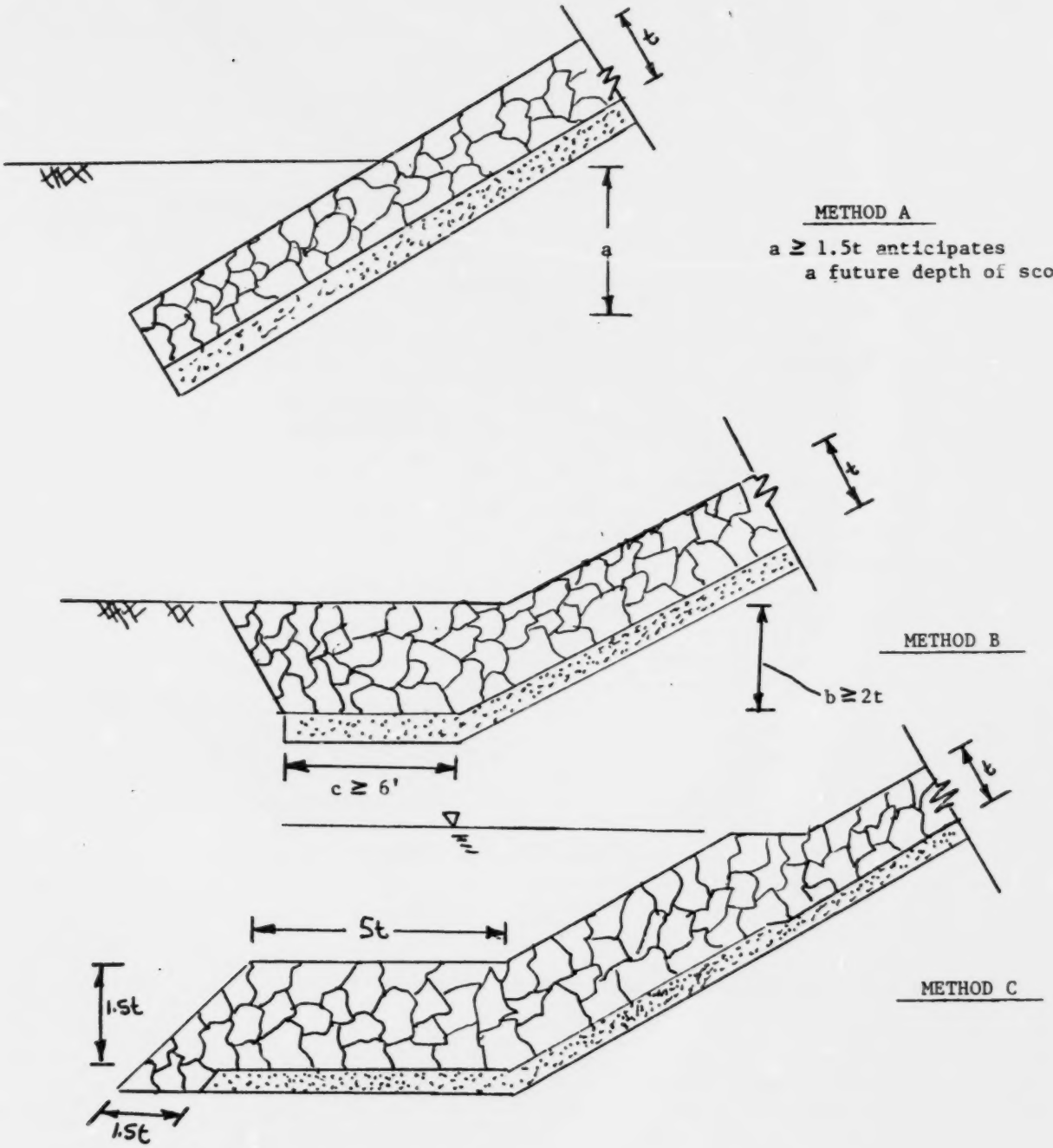


Figure 2-6. Toe Protection Alternatives

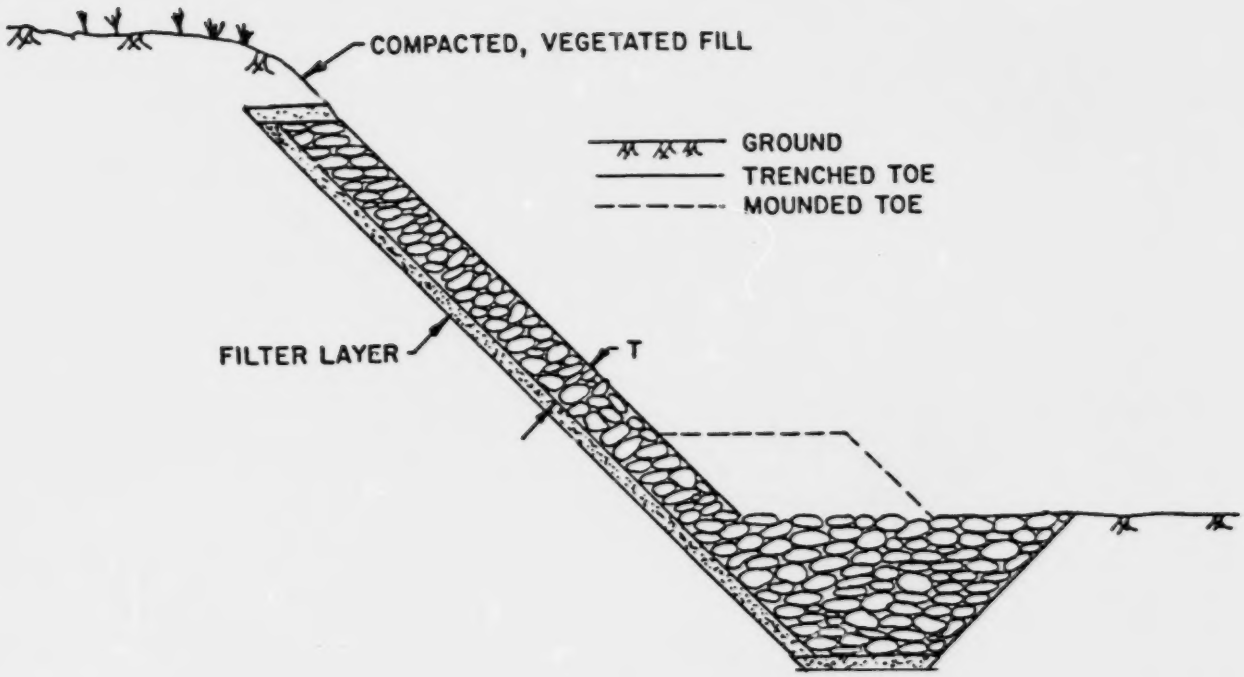


Figure 2-7. Toe Protection (taken from reference #13)

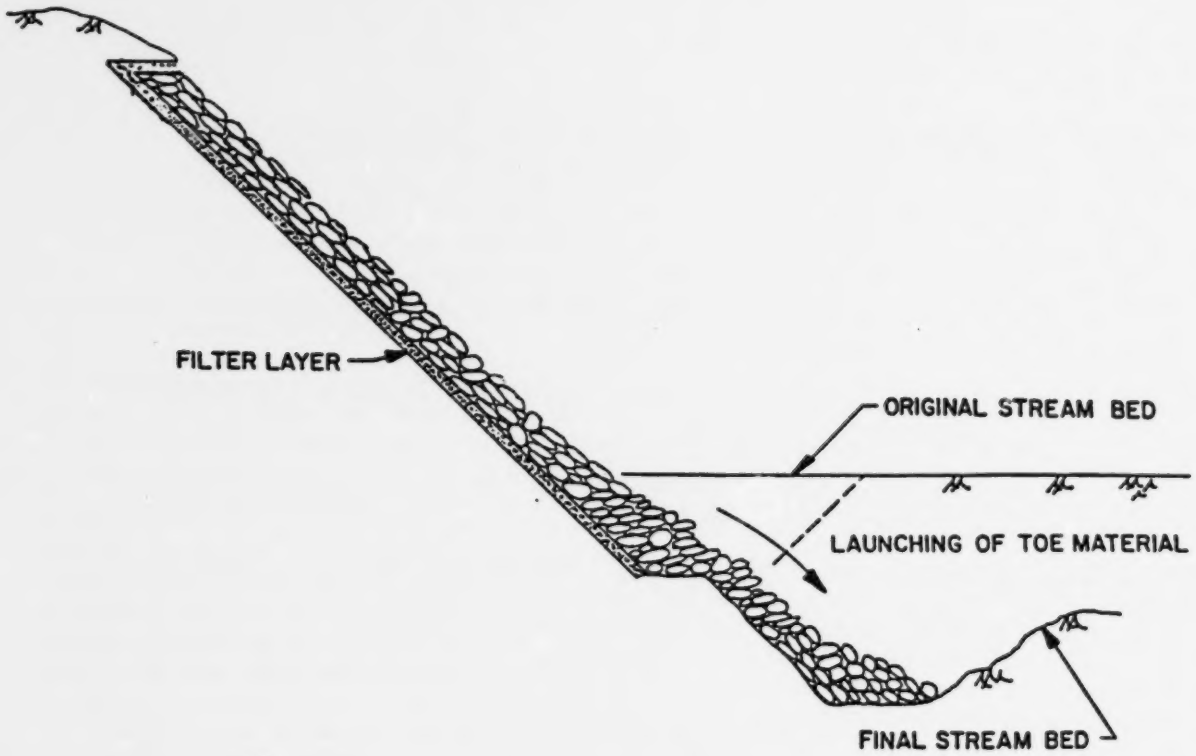


Figure 2-8. Launching Toe Material (from reference 13)

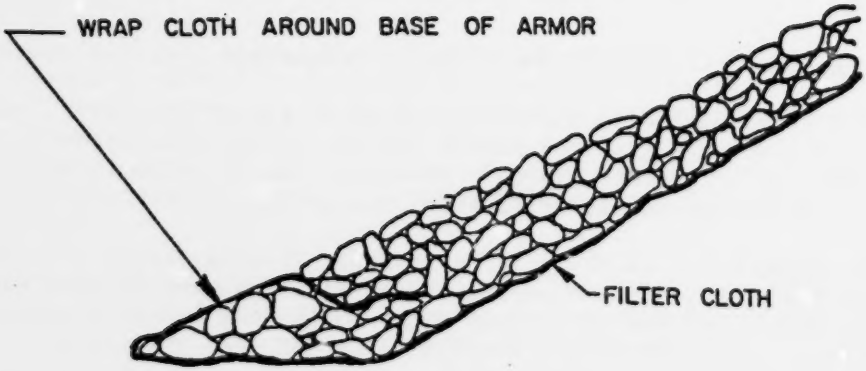


Figure 2-9. "Dutch Toe" (reference 13)

$$d15b > D15R/40 \qquad (2\text{-}5a)$$

$$D15R/5 < d85b \qquad (2\text{-}5b)$$

where,

d85b = particle size of bedding where 85% of the gradation by weight is smaller than this size

D15R = dimension of riprap where 15% of the gradation by weight is smaller than this size

d15b = particle size of bedding where 15% of the gradation by weight is smaller than this size

No published guidelines exist for bedding. One design rule often used is equation 2-6. This is the same as the basic filter design rule. The bedding-riprap system does not act like a base-filter system because the riprap is too thin to act like a filter. Riprap thickness is usually 1-1.5 times the maximum riprap particle size. The thickness of a filter is 10 to 100 times and more of the maximum filter particle size and consequently has many void openings. The gravel particles must be heavy enough to resist movement on their own. The filter rule seems to produce bedding large enough to be stable. One advantage in using this rule is as more severe conditions require larger riprap the bedding particles also become larger. If bedding needs to be permeable, a maximum limit of 5% nonplastic fines should be allowed. Bedding is generally 6" to 12" thick. The 6" thickness is used for smaller riprap and the 12" thickness for larger rock. This thickness is increased by 50% when the riprap is placed underwater than is more than 3 feet deep.

J. Filter Selection Criteria. A filter is used when base materials may pipe through the riprap. A decision will need to be made as to whether a piping potential exists. Answering the following questions may help to decide whether a filter is needed.

1. Is there seepage through the banks or foundation into the channel?

2. Will seepage emerge at the soil surface at a high gradient? It requires a seepage gradient over 1 vertically and usually over 0.5 horizontally to produce piping. Gradients due to drawdown do not produce piping unless stratification can produce artesian pressures.

3. Will piping occur if there is no riprap? Placing riprap on a surface is not going to produce a piping potential where none existed before. Is the soil resistant to piping? Some soils have a high resistance to piping. Clay and clayey soils (CL, CH, SC, GC) are piping resistant if the clay is not dispersed. Seepage flow through soils with significant fines content (ML, MH, SM, GM) are too low to cause piping except through cracks and voids. Well graded sands and gravels resist piping.

4. Where might piping occur under riprap? The most likely places are along streambanks in strata of uniform fine sands with artesian pressure. These locations can be identified during a geologic investigation or are often visible along the toe of a streambank. Other places where critical piping may occur is in a plunge pool below a conduit outlet or along the downstream toe of a dam. These areas are critical to dam safety and should be handled conservatively.

If careful consideration of seepage gradients and soils shows no piping potential exists, then filter may note be needed. If it is determined that a filter is necessary, the filter should be designed using Soil Mechanics Note #1.

K. Granular Filters. Equation 2-6 (from reference #3) below indicates the relationship necessary between layers of filter, or between the filter and the riprap, or between the filter and the base material. The left side of the inequality is intended to prevent piping through the filter, the center portion provides for adequate permeability for structural bedding layers, and the right portion provides a uniformity criteria. Equation 2-7 gives an additional guideline for riprap/filter compatibility.

$$\frac{D15 \text{ (coarser layer)}}{d85 \text{ (finer layer)}} < 5 < \frac{D15((\text{coarser layer})}{d15 \text{ (finer layer)}} < 40 \qquad (2\text{-}6)$$

$$d50 \text{ (finer layer)} > D50 \text{ (coarser layer)}/40 \qquad (2\text{-}7)$$

$$d5 \text{ (finer layer)} > \#200 \text{ sieve} \qquad (2\text{-}8)$$

If a single layer of filter material will not satisfy the filter requirements, one or more additional layers of filter material must be used. The grain size curves for the various layers should be approximately parallel to minimize the infiltration of fine material from the finer layer to the coarser layer. Not more than 5 percent of the filter material should pass the No. 200 sieve. Form SCS-ENG-80 in Appendix A can be used in designing an appropriate granular filter. The thickness of the filter blanket should range from 6 inches to 15 inches for a single layer, or from 4 to 8 inches for individual layers of a multiple layer blanket. Where gradation curves of adjacent layers are approximately parallel, the thickness of the blanket layers should approach the minimum. The thickness of individual layers should be increased above the minimum proportionately as the gradation curve of the material comprising the layer departs from a parallel pattern.

The thickness of the filter layer should be increased by 50% in all sections when the filter is placed underwater in water deeper than 3 feet to provide for uncertainties associated with this type of placement.

L. Geotextiles. Synthetic fabric filters have found considerable use as alternatives to granular filters. The primary justification for fabric filter over a granular filter is economic. Geotextiles may be less costly, especially where a good source of gravel is not convenient. Many manufacturers offer an extensive line of geotextiles. Care should be taken to select the appropriate

one for the site. The following lists give the advantages and disadvantages for fabric filters.

Advantages:

1. Installation is generally quick and labor-efficient.

2. Geotextiles may be less costly than granular filters.

3. Geotextiles have consistent and more reliable material quality.

4. Geotextiles have good inherent tensile strength.

5. Local availability of suitable granular filter material is no longer a design consideration when using fabric filters.

Disadvantages:

1. Geotextiles can be difficult to lay underwater.

2. Installation of some fabrics must be undertaken with care to prevent undue ultraviolet light exposure.

3. The life of the fabric in a soil environment is as yet unproven over the lifetime of a normal engineering project.

4. Bacterial activity within the soil or upon the filter can control the hydraulic responses of a fabric filter system.

5. Experimental evidence indicates that when channel banks are subjected to wave action, non-cohesive bank material has a tendency to migrate downslope beneath fabric filters; this tendency was not observed with granular filters.

6. Geotextiles may induce translational or modified slump failures when used under rock riprap installed on steep slopes.

7. Geotextiles may be subject to plugging under certain conditions such as bi-directional flow.

The function of fabric filters is to provide both drainage and filtration. In other words, the fabric must allow water to pass (drainage) while retaining soil properties (filtration). Both functions must be considered and perform properly during the design life of the measure. Filter fabrics, like granular filters, require engineering design. Unless proper fabric piping resistance, clogging resistance, and construction strength requirements are specified, it is doubtful that desired results will be obtained. Installation of the fabric must be monitored closely as well for a successful measure. Tips for successful installation are given below.

1. Heavy riprap may stretch the cloth as it settles, eventually causing bursting of the fabric in tension. A 4 to 6 inch layer of gravel

bedding should be placed on the fabric for riprap dropped more than 3 feet.

2. The filter cloth should not extend channelward of the riprap layer. It should be wrapped around the toe material as illustrated in Figure 2-9. This is sometimes called a "Dutch Toe".

3. Adequate overlaps must be provided between individual fabric sheets. For lightweight revetments this can be as little as 18 inches, and may increase to as much as 3 feet for large underwater revetments.

4. The geotextile should be overlapped during placement to eliminate tension and stretching under settlement.

5. Securing pins with washers are recommended at 2 to 5 foot intervals along the midpoint of the overlaps.

6. Proper stone placement on the filter requires beginning at the toe and proceeding up the slope. Dropping stone from heights greater than 2 feet can rupture fabrics (greater drop heights are allowable under water). A 6" thick layer of sand/gravel will cushion the impact and protect the fabric as the rock is dropped.

7. Non woven geotextile should be used on slopes steeper than 3:1 to minimize sliding.

8. The surface on which the geotextile is placed should be reasonably smooth, and free of holes, depressions, projections, mud and running water.

9. The length of the geotextile should be placed parallel to the direction of flow.

Detailed criteria for the design of geotextile filters are presented in reference 18. SCS criteria for selection of filter fabrics is contained in the instructions for the construction and material specifications for geotextiles. In the Midwest, these are specifications MIDWEST-217, Geotextiles and MIDWEST 308, Geotextiles, Woven and Non-Woven, respectively. Reference #23 also offers information on geotextiles and their use.

CHAPTER 3. PROTECTION AT CONDUIT INLETS AND OUTLETS

A. SCOUR PROTECTION FOR PIPE INLETS AND ORIFICES

Scour around inlets is normally not a serious problem. Scour holes are relatively small. Research has shown that scour holes do reach a maximum size for a given discharge. Without protection, a scour hole will develop at a given location of the size predicted by equation 3-1. Scour hole depth and radius can be predicted for non-cohesive soils by Blaisdell's equations (from reference #32 or Design Note 1) below.

$$R = \left(0.15\ do + \frac{0.04\ Q}{(do)^{3/2}}\right)\left(\frac{do}{D50s}\right)^{1/5} \qquad (3\text{-}1)$$

$$S = \frac{1}{20}\left(\frac{Q}{(do)^{3/2}}\right) - D50s - 0.075\ do \qquad (3\text{-}2)$$

R = Radius of scour hole, feet
do = Orifice or pipe diameter, feet
Q = design discharge, cfs
D50s = mean particle diameter of the soil, feet
S = Depth of scour hole, feet

Where inlet scour holes are not acceptable in the design of inlet approach slopes, control of scour can be controlled by a reinforced concrete, grouted or loose riprap apron. Reinforced concrete may be preferable due to high velocities near the inlet edge. This may be in the form of a precast end section, used as an entrance to a pipe. A minor amount of riprap may be needed at the transition from the end section to the earthen channel if turbulence is expected.

Where loose riprap is to be used, special attention to stone size and placement is required within one pipe diameter (do) of the inlet. Since velocities dramatically increase as the inlet edge is approached, riprap within one pipe diameter (do) of the inlet edge shall be 1.3 times the D50 from equation (3-3). Also, the longest dimension of the stones shall be placed in the vertical direction to maximize stone weight and reduce uplift forces on the stone. The mean stone diameter (D50) of riprap farther than one pipe diameter from the inlet edge is given by equation (3-3). The radius of the protection should not be less than that determined by equation (3-1).

If the riprap apron is grouted, the minimum mean stone diameter (D50) given in equation (3-3) is for rock within one pipe diameter of the edge of the pipe. Grouted riprap further than one pipe diameter from the inlet edge of the pipe may have a mean stone diameter of not less than 0.4 times D50.

$$D50 = \left(\frac{0.05Q}{(do)^{3/2}}\right) - 0.075\ do \qquad (3\text{-}3)$$

D50 = minimum mean stone diameter of riprap

B. RIPRAP LINED PLUNGE POOL OR STILLING BASIN

Preformed stilling basins are normally recommended where materials eroded from plunge pools can cause downstream damage to the channel or the environment. Riprap lining is recommended for basins in erodible soils or where seepage occurs in the basin. Basins are normally required for cantilevered outlets on dams, grade stabilization structures, etc. Design guidelines for stilling basins are given in Design Note #6 (reference #21).

C. PIPE OUTLET PROTECTION (for Outlets on Grade)

Site conditions do not always allow for use of a stilling basin. However, some protection is needed to prevent erosion and damage to the outlet by undercutting at locations such as road crossing culverts, stream crossings, and drainage culverts.

Special problems arise when the conduit is square or arch pipe. The use of equivalent diameter (calculated solely by equal flow areas) has not been satisfactory for determining outlet proteciton. The problem includes the fact that do/TW is a submergence factor. A later section in this chapter describes use of Discharge Intensity to relate round pipe to square and arch pipe.

Three alternatives are available where the outlet has the same elevation as the channel bottom. These may be adapted to site conditions. The median stone size (D50) is determined by equation (3-4). This equation can be mathematically simplified to the form expressed in equation 3-4a.

$$\frac{D50}{do} = C\,\frac{do}{TW}\left(\frac{Q}{do^{5/2}}\right)^{4/3} \qquad (3\text{-}4)$$

$$D50 = \frac{C}{TW}\left(\frac{Q}{do}\right)^{4/3} \qquad (3\text{-}4a)$$

D50 = Median stone size, feet
do = Pipe diameter, feet
TW = Tailwater depth above the invert of the culvert, feet
C = Constant for type of protection (See descriptions below for alternatives)
Q = Discharge, cfs

After equation 3-4 or 3-4a has been solved for one of the three alternatives, Table 2-2 should be used to expand the D50 size to a complete gradation.

Alternative #1: A horizontal blanket can be used where there is no defined channel below the outlet. The blanket shall have zero grade. The end of the blanket shall be flush with existing channel or ground surface. The constant C for equation (3-4) or (3-4a)shall be 0.020. The shape shall conform to that in Figure 3-1. The length of riprap protection downstream of an outlet is dependent on tailwater (TW) depth. It is defined by equations (3-5) and (3-6).

$$\text{Where } TW \geq 0.5\,do, \quad L1 = 3\,do\,(Q/(do)^{5/2}) \qquad (3\text{-}5)$$

$$\text{Where } TW < 0.5\,do, \quad L2 = 1.8\,do\,(Q/(do)^{5/2}) + 7do \qquad (3\text{-}6)$$

L1,L2 - Length of protection, feet
do - Pipe diameter or equivalent diameter, feet
Q - Discharge, cfs
TW - Tailwater depth above the invert of the culvert, feet

In many cases, tailwater will vary and a combination of the two lengths and blanket shapes shall be used as shown in Figure 3-1.

Alternative #2: A preformed scour hole may be used. These scour holes are shallower than stilling basins designed using Design Note 6. When lined with riprap, it provides both vertical and lateral expansion downstream of an outlet to permit dissipation of excess kinetic energy in turbulence rather than direct attack on the boundaries. This allows for a reduction in the stone size over the horizontal blanket or the lined channel expansion. A further stone size reduction can be achieved by deepening the scour hole.

$$\text{for } S = 0.5\,do \quad C = 0.0125 \qquad (3\text{-}7a)$$

$$\text{for } S \geq do \quad C = 0.0082 \qquad (3\text{-}7b)$$

where S - Depth of scour hole, feet (E'qn 3-2)
do - Pipe diameter or equivalent diameter, feet
C - Constant used in equation (2-4); C may be varied for other values of S

For preformed scour hole dimensions, see Figure 3-2. If the bottom width of the exit channel is less than or equal to the top width of the scour hole, the riprap should be extended up the sides to the tailwater depth. The designer may wish to extend the riprap up to the tailwater depth regardless of the channel bottom width. A berm on the channel side slopes is an alternative also.

Alternative #3: A lined channel expansion is normally used where a channel continues beyond the outlet of the culvert. The constant (C) for equation (3-5) is 0.0160. The configuration of the lined channel expansion is shown in Figure 3-3.

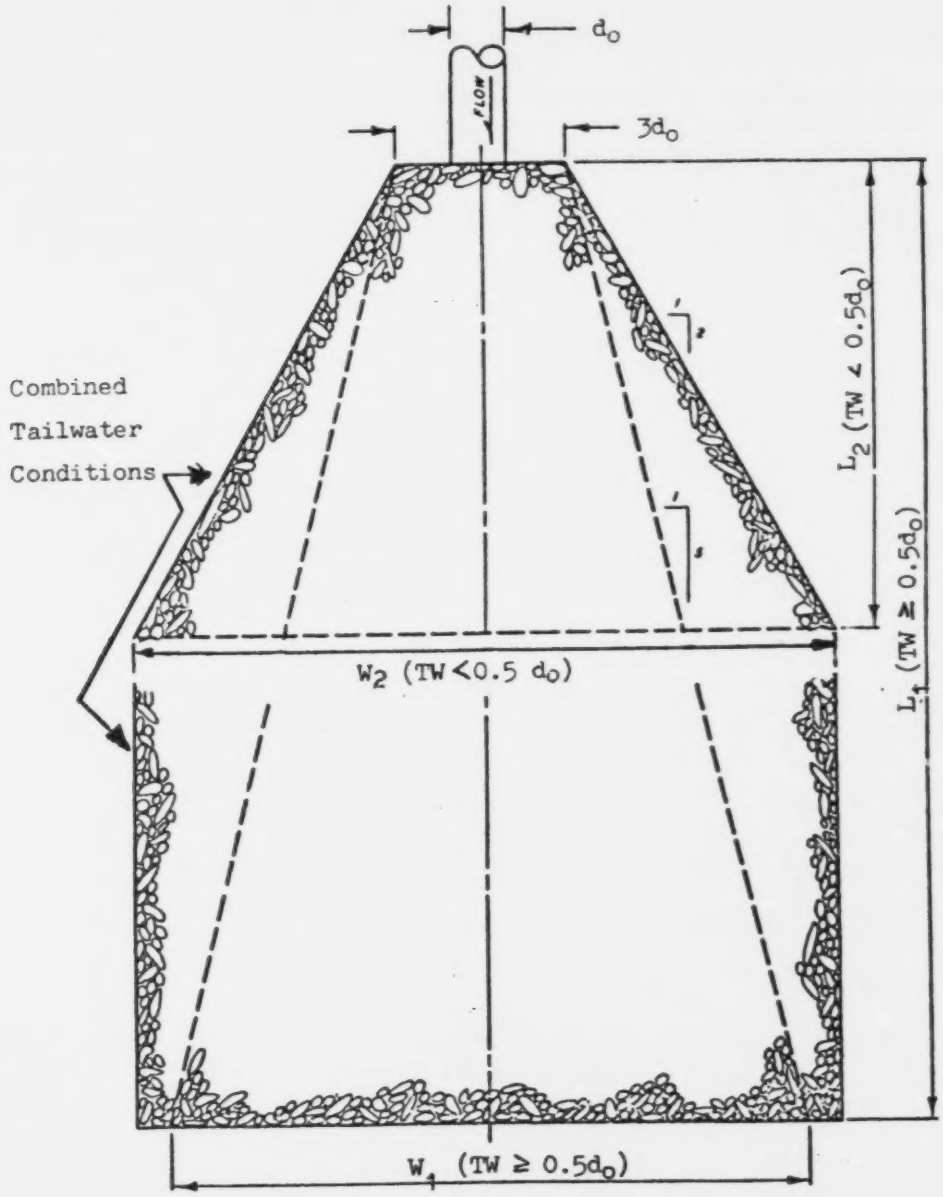


Figure 3-1. Recommended configuration of riprap blanket subject to minimum and maximum tailwaters

At some point it is better to use traditional energy dissipaters rather than riprap protection for economical and practical reasons. Both approaches should be considered where large sizes and volumes of rock are required.

Arch Pipes, Square or Rectangular Conduits:

Research has recently been done at Colorado State University (references 25 and 26) on scour at culvert outlets. Use of arch, square and rectangular culverts were compared to use of circular culverts. The pipes were compared to each other through use of a term called Discharge Intensity (D.I.). This value is defined in the following equation.

$$D.I. = Q/(A(gR)^{0.5}) \qquad (3\text{-}8)$$

where,

D. I. = Discharge intensity (dimensionless)
A = area of flow in square feet
Q = discharge in cfs
g = gravitational constant, 32.2 ft/sec^2
R = hydraulic radius of conduit, feet

This equation relates the shape of the culvert to the discharge. The study results showed that the scour hole's depth, length and width increased with increasing D.I. For pipe arches, the scour length increased 3-12% over that experienced with a circular culvert. However, with rectangular and square culverts, the length of the scour increased 10-30% over that experienced by a circular conduit with a similar D.I. The National Headquarters is in the process of incorporating this data into a design procedure. In the meantime, it is well to be aware that alternate pipe shapes increase the dimensions of the scour.

Furthermore, research by Anderson (reference 24) showed that the typical conical scour hole would increase to a scour hole with beaching (see Figure 3-4) for high flows. He developed the relationship given in equation 3-9. Beaching did not occur if the inequality in equation 3-9 was satisfied.

$$Q/(gD^5)^{0.5} \leq 1 + (25*d50/D) \qquad (3\text{-}9)$$

where,
Q = discharge in cfs
D = diameter of pipe in feet
d50 = median size of bed material or rock protection, feet
g = gravitational constant, 32.2 ft/sec^2

The tables in this chapter are provided to facilitate computations of the Discharge Intensity. The area and perimeter of arch pipe are given also.

Multiple Outlets:

In many situations more than one conduit is used to pass the flow. In these cases, it is important to be certain that the outlet protection is adequate for all the conduits.

NOTE: If bottom width of exit channel is less than or equal to the top width of the scour hole, riprap should be extended up the sides to the tailwater depth.

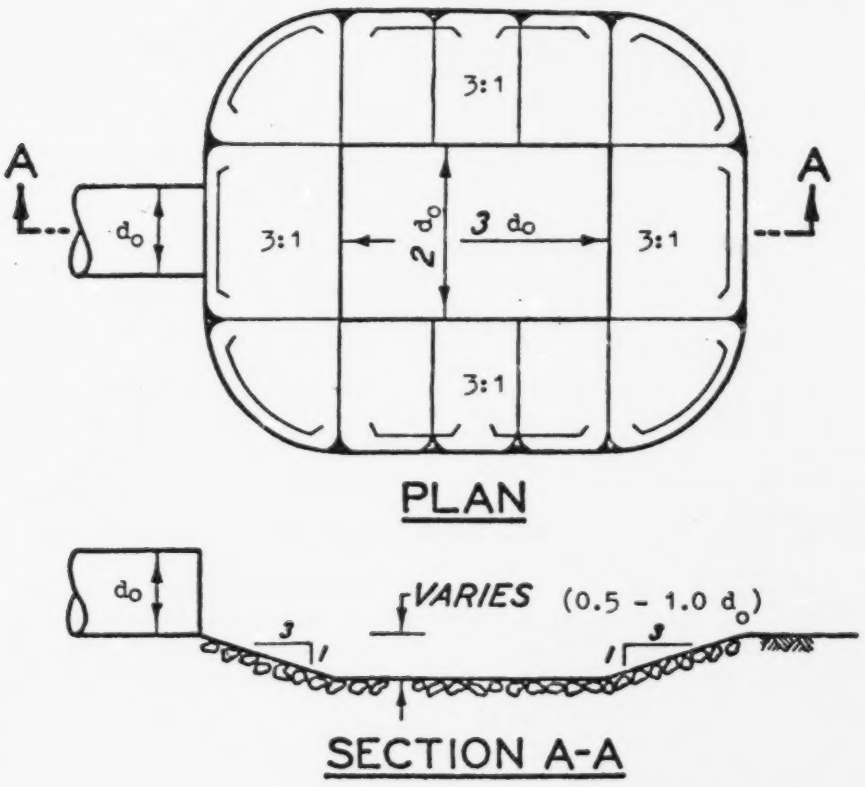


Figure 3-2. Preformed scour hole

NOTE: The top of lining shall be the tailwater elevation. The end of the expansion shall conform to the existing downstream section and flowlines shall match.

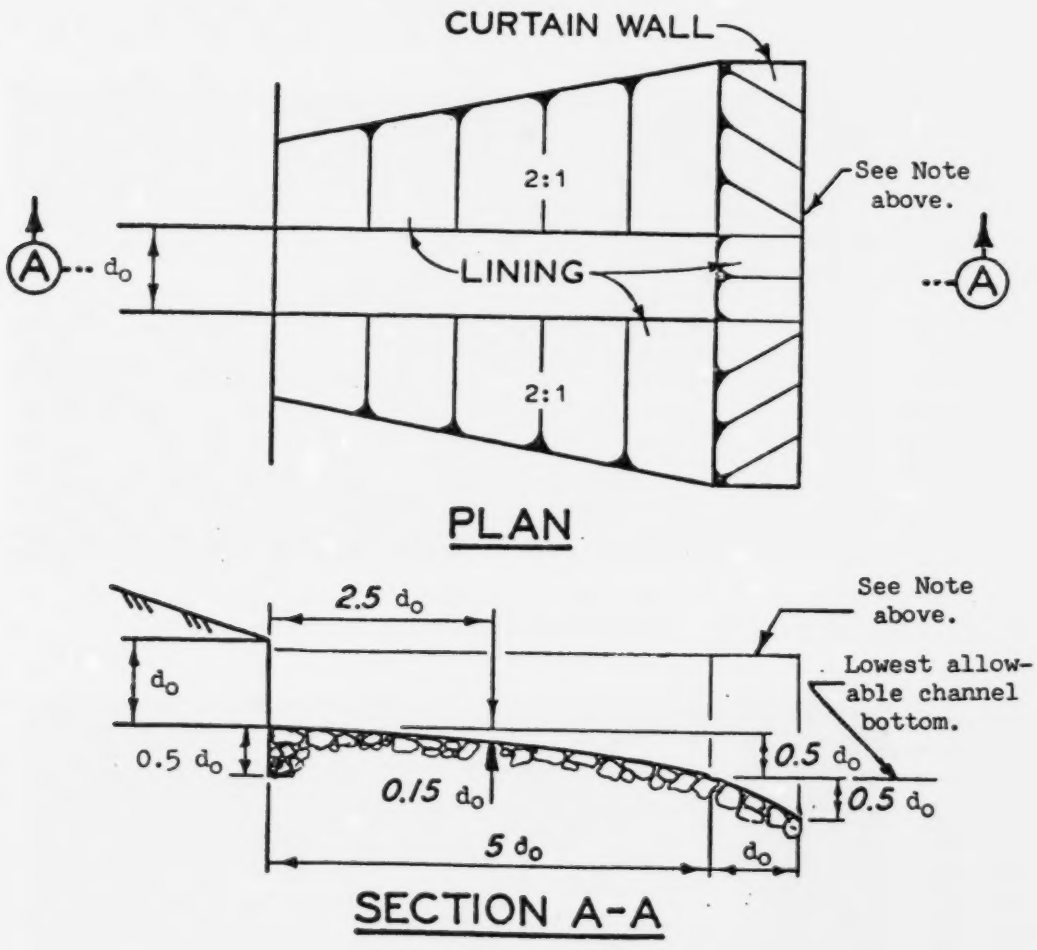


Figure 3-3. Culvert Outlet erosion protection, lined channel expansions

In the situation where two or more conduits are laid along the same orientation, such as in Figure 3-5, one needs to figure the Discharge Intensity (see equation 3-8) for each conduit separately. These values should be added to obtain a total D.I. value. Sum the discharges carried by the conduits for a total discharge. Using the information in Table 3-1, determine the diameter of a single round conduit that has the same Discharge Intensity as the sum of the multiple conduits. This equivalent diameter can be used in other design equations to calculate the size of the protection. Equation 3-9 should always be checked to minimize the chances of beaching occurring.

Another situation exists where two or more conduits discharge at the same point from different orientations. The equations to design the protection should be applied separately to each conduit. On a plan view, the separate dimensions calculated for each conduit should be plotted and scaled off. Then the "worst" case can be identified and a design configuration selected. Equation 3-9 should be calculated to check for possible beaching.

Table 3-1 is offered to facilitate calculating the Discharge Intensity. Additional tables are provided for the area and perimeter of arch pipe. Overall it is believed that an increase of 25-35% in rock size and length of protection should be reasonable for most multiple outlet situations.

Table 3-1. Parameters for Round Conduits

Diameter (inches)	Area (sq ft)	Perimeter (feet)	Hydraulic Radius	0.5 A(gR)
12	0.785	3.142	0.25	2.23
15	1.227	3.927	0.3125	3.89
18	1.767	4.712	0.375	6.14
24	3.142	6.28	0.50	12.61
30	4.909	7.85	0.625	22.02
36	7.069	9.425	0.75	34.74
42	9.621	11.00	0.875	51.068
48	12.566	12.56	1.0	71.306
54	15.904	14.14	1.125	95.721
60	19.635	15.708	1.25	124.57

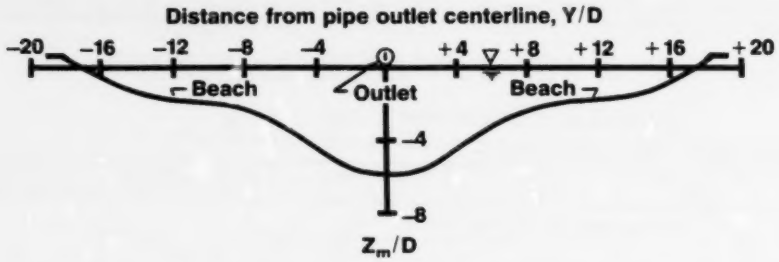


Figure 3-4. Cross-section of Scour Hole with Beaching (reference #24)

Figure 3-5. Multiple conduits with the same orientation

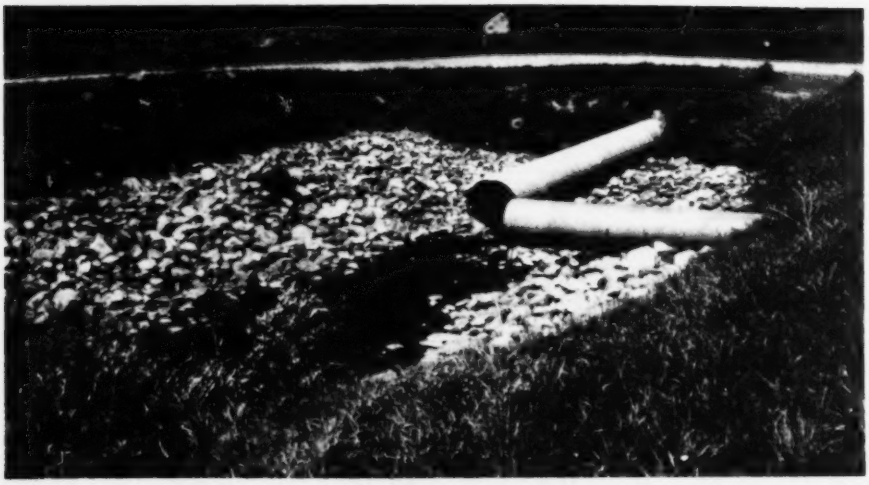


Figure 3-6. Multiple conduits with different orientation

Table 3-2.

HYDRAULIC FACTORS FOR
CORRUGATED METAL PIPE-ARCHES AND MULTI-PLATE PIPE-ARCHES

Size (in)	Rise (ft)	Span (ft)	Area (sq ft.)	Periphery (ft.)	Hydraulic Radius Flowing Full (ft)	Round Pipe of Equal Periphery (in.)
Corrugated Metal Pipe-Arches						
11 x 18	0.92	1.50	1.1	3.93	0.280	15
13 x 22	1.08	1.83	1.6	4.71	0.340	18
16 x 25	1.33	2.08	2.2	5.50	0.400	21
18 x 29	1.50	2.42	2.8	6.28	0.446	24
22 x 36	1.83	3.00	4.4	7.85	0.561	30
27 x 43	2.25	3.58	6.4	9.42	0.679	36
31 x 50	2.58	4.17	8.7	11.00	0.791	42
36 x 58	3.00	4.83	11.4	12.57	0.907	48
40 x 65	3.33	5.42	14.3	14.14	1.011	54
44 x 72	3.67	6.00	17.6	15.71	1.120	60
Multi-Plate Pipe-Arches						
55 x 73	4.58	6.08	22	17.28	1.273	66
57 x 76	4.75	6.33	24	18.06	1.329	69
59 x 81	4.92	6.75	26	18.85	1.379	72
61 x 84	5.08	7.00	28	19.64	1.426	75
63 x 87	5.25	7.25	31	20.42	1.518	78
65 x 92	5.42	7.67	33	21.21	1.556	81
67 x 95	5.58	7.92	35	21.99	1.592	84
69 x 98	5.75	8.17	38	22.78	1.668	87
71 x 103	5.92	8.58	40	23.56	1.698	90
73 x 106	6.08	8.83	43	24.35	1.766	93
75 x 112	6.25	9.33	46	25.13	1.830	96
77 x 114	6.42	9.50	49	25.92	1.890	99
79 x 117	6.58	9.75	52	26.70	1.948	102
81 x 123	6.75	10.25	55	27.49	2.001	105
83 x 128	6.92	10.67	58	28.27	2.052	108
85 x 131	7.08	10.92	61	29.06	2.099	111
87 x 137	7.25	11.42	64	29.85	2.144	114
89 x 139	7.42	11.58	67	30.63	2.187	117
91 x 142	7.58	11.83	71	31.42	2.260	120
93 x 148	7.75	12.33	74	32.20	2.298	123
95 x 150	7.92	12.50	78	32.99	2.364	126
97 x 152	8.08	12.67	81	33.77	2.399	129
100 x 154	8.33	12.83	85	34.56	2.459	132
101 x 161	8.42	13.42	89	35.34	2.518	135
103 x 167	8.58	13.92	93	36.13	2.574	138
105 x 169	8.75	14.08	97	36.91	2.628	141
107 x 171	8.92	14.25	101	37.70	2.679	144
109 x 178	9.08	14.83	105	38.48	2.729	147
111 x 184	9.25	14.33	109	39.27	2.776	150
113 x 186	9.42	14.50	113	40.06	2.821	153
115 x 188	9.58	15.67	118	40.84	2.889	156
118 x 190	9.83	15.83	122	41.63	2.931	159
119 x 197	9.92	16.42	126	42.41	2.971	162
121 x 199	10.08	16.58	131	43.20	3.032	165

Figure 3-7.

DIMENSIONS OF CORRUGATED METAL PIPE-ARCHES

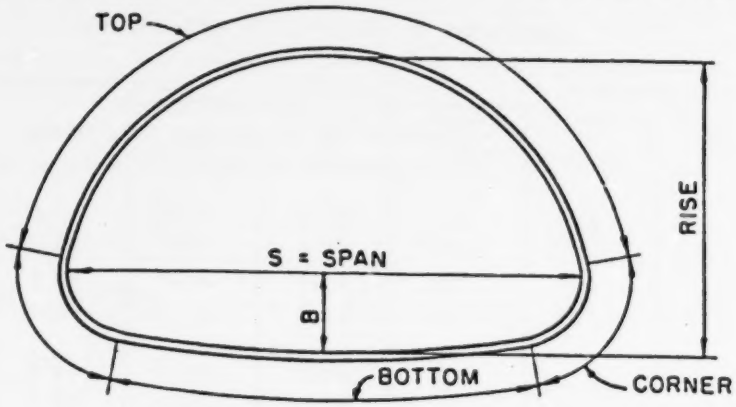
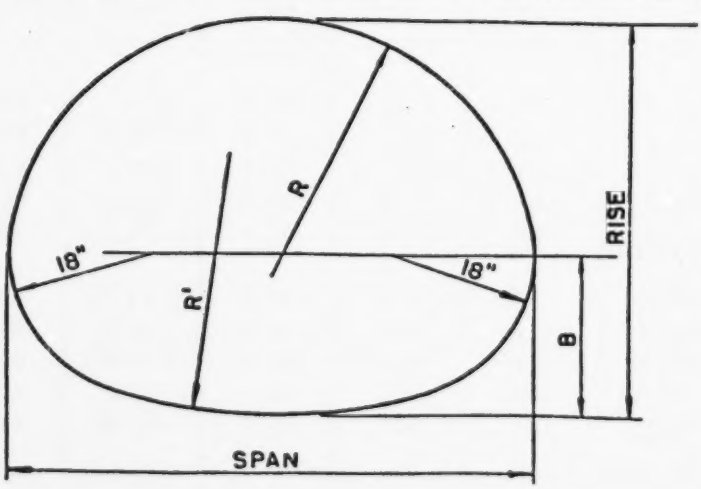


TABLE II

SPAN IN INCHES *	RISE IN INCHES *	"B" IN INCHES *	AREA IN SQ. FT.	DIAM. PIPE OF EQUAL PERIPHERY IN INCHES
18	11	4 1/2	1.1	15
22	13	4 3/4	1.6	18
25	16	5 1/4	2.2	21
29	18	5 1/2	2.8	24
36	22	6 1/4	4.4	30
43	27	7	6.4	36
50	31	8	8.7	42
58	36	9 1/4	11.4	48
65	40	10 1/2	14.3	54
72	44	11 3/4	17.6	60

* MANUFACTURING TOLERANCE = PLUS OR MINUS ONE INCH

DIMENSIONS OF CORRUGATED METAL MULTI-PLATE PIPE-ARCHES



SHEET 3 OF 4 3-L-25842

Table 3-3.

DIMENSIONS OF MULTI-PLATE PIPE-ARCHES

Nominal Dimensions				Layout Dimensions in Inches				
Span	Rise	Area in Sq. Ft.	Total Periphery in Pi In.	B	Rise	1/2 Span	R	R'
6'-1"	4'-7"	22	66	21.0	55.0	36.5	36.8	76.3
6'-4"	4'-9"	24	69	20.5	57.1	38.0	38.1	98.6
6'-9"	4'-11"	26	72	22.0	58.9	40.6	41.0	83.5
7'-0"	5'-1"	28	75*	21.4	61.1	42.1	42.3	104.2
7'-3"	5'-3"	31	78	20.8	63.2	43.5	43.5	136.2
7'-8"	5'-5"	33	81	22.4	65.0	46.2	46.5	109.8
7'-11"	5'-7"	35	84	21.7	67.2	47.6	47.7	137.9
8'-2"	5'-9"	38	87*	20.9	69.4	48.9	48.9	182.9
8'-7"	5'-11"	40	90	22.7	71.1	51.7	51.9	141.0
8'-10"	6'-1"	43	93	21.9	73.3	53.0	53.0	178.7
9'-4"	6'-3"	46	96	23.8	75.1	55.9	56.2	144.6
9'-6"	6'-5"	49	99	22.9	77.3	57.1	57.3	177.5
9'-9"	6'-7"	52	102	21.9	79.5	58.3	58.3	227.7
10'-3"	6'-9"	55	105	24.0	81.2	61.3	61.5	178.3
10'-8"	6'-11"	58	108	26.1	82.9	64.2	64.9	153.2
10'-11"	7'-1"	61	111	25.1	85.1	65.5	65.9	180.4
11'-5"	7'-3"	64	114*	27.4	86.9	68.4	69.4	157.9
11'-7"	7'-5"	67	117	26.3	89.1	69.7	70.2	183.2
11'-10"	7'-7"	71	120	25.2	91.3	70.9	71.1	216.4
12'-4"	7'-9"	74	123	27.5	93.0	73.9	74.7	186.5
12'-6"	7'-11"	78	126	26.4	95.2	75.1	75.5	216.8
12'-8"	8'-1"	81	129	25.2	97.4	76.2	76.4	257.4
12'-10"	8'-4"	85	132*	24.0	99.7	77.2	77.3	314.7
13'-5"	8'-5"	89	135	26.4	101.3	80.4	80.7	254.8
13'-11"	8'-7"	93	138	28.9	103.0	83.6	84.4	220.7
14'-1"	8'-9"	97	141	27.6	105.2	84.7	85.1	254.1
14'-3"	8'-11"	101	144	26.3	107.5	85.7	85.9	297.6
14'-10"	9'-1"	105	147	28.9	109.2	88.9	89.6	254.3
15'-4"	9'-3"	109	150*	31.6	110.8	92.0	93.4	226.8
15'-6"	9'-5"	113	153	30.2	113.1	93.2	94.0	255.7
15'-8"	9'-7"	118	156	28.8	115.3	94.2	94.7	291.5
15'-10"	9'-10"	122	159	27.5	117.6	95.2	95.5	338.1
16'-5"	9'-11"	126	162	30.1	119.2	98.5	99.2	290.9
16'-7"	10'-1"	131	165*	28.7	121.5	99.5	99.9	332.7

Dimensions are to inside crests and are subject to manufacturing tolerances.

*These structures are preferred because they give greatest area for given number of plates and bolts per ring. Each structure of less span than those marked provides correspondingly less area for the same number of plates and bolts.

A

DESIGN FORM A
SCOUR PROTECTION FOR INLETS
MINNESOTA

Project Sample Problem A County Polk

By SMJ Date 4/19/89 Ck'd By ABJ Date 4/20/89

Description of Situation:
Turbulence expected in silty soil. Flush headwall.

Pipe Diameter (do) 36" = 3ft. Peak Discharge (Q) 37 cfs

Median soil particle size (D50s) 0.005 mm (in feet) 1.6404×10^{-5}

Pipe diameter to 3/2 power ($do^{3/2}$) 5.20

Radius of scour hole predicted by equation 3-1:

$$R = \left(\frac{0.040}{0.15do + \frac{0.040}{(do)^{3/2}}}\right)\left(\frac{do}{D50s}\right)^{1/5} = \left(.15(3') + \frac{.04(37\ cfs)}{5.20}\right)\left(\frac{3}{1.6404 \times 10^{-5}}\right) = 8.29\ ft.$$

Depth of Scour hole (S) by Equation 3-2:

$$S = \left(\frac{0.050}{(do)^{3/2}}\right) - D50s - 0.075(do) = \frac{.05(37)}{5.20} - \cancel{1.6404 \times 10^{-5}}^{\text{negligible}} - .075(3)$$

$= .131$ ft.

Mean stone diameter of riprap (D50) from equation 3-3:

$$D50 = \left(\frac{0.050}{(do)^{3/2}}\right) - 0.075(do) = \left(\frac{.05(37)}{5.20}\right) - .075(3) = .131\ ft = 1.57"$$

1.3 x D50 = 2.04 inches

Riprap Gradation:

		(Table 2-2)	(Using D50)	(Using D50 x 1.3)
D100	-	1.5-2.0 D50	2¼" - 3"	3" - 4"
D85	-	1.3-1.8 D50	2" - 2¾"	2½" - 4"
D50	-	1.0-1.5 D50	1½" - 2¼"	2" - 3"
D15	-	0.3-0.5 D50	½" - ¾"	½" - 1"

band is narrow; adjust on ENG-80 by what's locally available

Note: The riprap within one pipe diameter of the inlet is to be the larger gradation where the median rock is (1.3 x D50).

DESIGN FORM A (Sheet 2 of 2)
SCOUR PROTECTION FOR INLETS

Filter/Bedding Requirements:
No seepage or leaching expected. Filter not required.
Riprap thickness is sufficient here as bedding also.

Thickness of Riprap: (see Chapter 2, Section E)

1.25 x $D100_{MAX}$ - 1.25 * 4" = 5" (minimum of 9-12 inches) use 12"

Placing underwater? Yes (No) Ice or wave attack? Yes (No)

Add 6-12" to the thickness if subject to ice or wave attack.
Increase thickness by 50% if placing in water greater than 3' deep.

C

DESIGN FORM C
PIPE OUTLET PROTECTION
MINNESOTA TR-3

Reference: Section C in Chapter 3 of MN TR-3

Project: Sample Problem C-1 County Aitkin

By SMJ Date 4/19/89 Ck'd By ABB Date 4/20/89

Pipe diameter (do) 36" = 3' Peak discharge (Q) 47 cfs

Tailwater (TW) 1.5' Soil median particle size (D50s) .005 mm = 1.64×10^{-5} ft.

$$D50 = \frac{C}{TW}\left(\frac{Q}{do}\right)^{4/3} \quad \text{(Eq'n 3-4a)}$$

D50 = .523' = 6¼"

Check Alternative Used:

[X] Alternative #1: Horizontal Blanket C=0.020 (see Figure 3-1)

For TW ≥ 0.5do, L1 = $3(do)\ (Q/(do)^{5/2})$ (Eq'n 3-5) = 27.1 ft.

For TW < 0.5do, L2 = $1.8do\ (Q/(do)^{5/2}) + 7do$ (Eq'n 3-6) =

[ ] Alternative #2: Preformed Scour Hole (see Figure 3-2)

S = $(0.05Q/(do)^{3/2})$ - D50s - 0.075do (Eq'n 3-2) S=_____

Select S = _____(must be ≥ S calculated here)

for S = 0.5 do C = 0.0125 (Eq'n 3-7a)

for S ≥ do C = 0.0082 (Eq'n 3-7b)

[ ] Alternative #3: Lined Channel Expansion (Figure 3-3) C=0.016

Riprap Gradation:

D100	1.5-2.0 x D50	9½" to 12½"
D85	1.3-1.8 x D50	8" to 11¼"
D50	1.0-1.5 x D50	6¼" to 9½"
D15	0.3-0.5 x D50	2" to 3"

Thickness of Riprap Layer: (see Chapter 2, Section E of MN TR-3)

$1.25 \times D100_{MAX}$ = 1.25 x 12.5 = 15.6" (minimum of 12 inches) use 18"

Filter/Bedding Requirements: use SMN1 and equations 2-6 and 2-7 to design filter/bedding. Geotextiles OK too.

C

DESIGN FORM C
PIPE OUTLET PROTECTION
MINNESOTA TR-3

Reference: Section C in Chapter 3 of MN TR-3

Project: Sample Problem C-2 County Aitkin

By SM²J Date 4/19/89 Ck'd By ~~ABS~~ Date 4/20/89

Pipe diameter (do) 36" = 3' Peak discharge (Q) 47 cfs

Tailwater (TW) 1.5' Soil median particle size (D50s) $\frac{.005}{mm}$ - 1.64×10^{-3} ft.

$$D50 = \frac{C}{TW}\left(\frac{Q}{do}\right)^{4/3} \quad \text{(Eq'n 3-4a)}$$

D50 = .323' = 4"

Check Alternative Used:

☐ Alternative #1: Horizontal Blanket C=0.020 (see Figure 3-1)

For TW ≥ 0.5do, L1 = 3(do) $(Q/(do)^{5/2})$ (Eq'n 3-5) =

For TW < 0.5do, L2 = 1.8do $(Q/(do)^{5/2})$ + 7do (Eq'n 3-6) =

☒ Alternative #2: Preformed Scour Hole (see Figure 3-2)

S = $(0.05Q/(do)^{3/2})$ - D50s - 0.075do (Eq'n 3-2) S= .227' = 2¾"

Select S = 6" (must be ≥ S calculated here)

for S = 0.5 do C = 0.0125 (Eq'n 3-7a) use C=.0125

for S ≥ do C = 0.0082 (Eq'n 3-7b)

☐ Alternative #3: Lined Channel Expansion (Figure 3-3) C=0.016

Riprap Gradation:

D100	1.5-2.0 x D50	6" to 8"
D85	1.3-1.8 x D50	5¼" to 7¼"
D50	1.0-1.5 x D50	4" to 6"
D15	0.3-0.5 x D50	1¼" to 2"

Thickness of Riprap Layer: (see Chapter 2, Section E of MN TR-3)

$1.25 \times D100_{MAX}$ = 1.25 x 8" = 10" (minimum of 12 inches) use 12"

Filter/Bedding Requirements: use SMN1 and equations 2-6 and 2-7 to design filter/bedding. Geotextiles OK too.

C

DESIGN FORM C
PIPE OUTLET PROTECTION
MINNESOTA TR-3

Reference: Section C in Chapter 3 of MN TR-3

Project: Sample Problem C-3 County Aitkin

By SM²J Date 4/19/89 Ck'd By ~~ABS~~ Date 4/20/89

Pipe diameter (do) 36" = 3ft. Peak discharge (Q) 47 cfs

Tailwater (TW) 1.5' Soil median particle size (D50s) .005 mm = 1.64×10^{-5} ft.

$$D50 = \frac{C}{TW}\left(\frac{Q}{do}\right)^{4/3} \quad \text{(Eq'n 3-4a)}$$

D50 = 0.418' = 5"

Check Alternative Used:

☐ Alternative #1: Horizontal Blanket C=0.020 (see Figure 3-1)

For TW ≥ 0.5do, L1 = $3(do)\ (Q/(do)^{5/2})$ (Eq'n 3-5) =

For TW < 0.5do, L2 = $1.8do\ (Q/(do)^{5/2}) + 7do$ (Eq'n 3-6) =

☐ Alternative #2: Preformed Scour Hole (see Figure 3-2)

S = $(0.05Q/(do)^{3/2})$ - D50s - 0.075do (Eq'n 3-2) S=_____

Select S = _____ (must be ≥ S calculated here)

for S = 0.5 do C = 0.0125 (Eq'n 3-7a)

for S ≥ do C = 0.0082 (Eq'n 3-7b)

☒ Alternative #3: Lined Channel Expansion (Figure 3-3) (C=0.016)

Riprap Gradation:

D100	1.5-2.0 x D50	7½" to 10"
D85	1.3-1.8 x D50	6½" to 9"
D50	1.0-1.5 x D50	5" to 7½"
D15	0.3-0.5 x D50	1½" to 2½"

Thickness of Riprap Layer: (see Chapter 2, Section E of MN TR-3)

$1.25 \times D100_{MAX}$ = 1.25 x 10" = 12½" (minimum of 12 inches) use 15"

Filter/Bedding Requirements: use SMN1 and equations 2-6 through 2-8 to design filter/bedding. Geotextiles OK too.

CHAPTER 4. PROTECTION FOR STRUCTURE INLETS AND OUTLETS

A. CHANNEL PROTECTION UPSTREAM FROM STRUCTURES

Normally channels upstream from grade or water control structures are level or have very flat grades. The velocities accelerate only in the vicinity of the weir. Therefore only a small portion of the channel is subject to higher velocities. Channel protection shall be provided adjacent to the structure weir for a minimum distance of two times the required flow depth for the weir. This is shown in equation form in equation (4-1). Equation (4-2) determines the median stone size (D50).

$$L1 = 2 \times H \qquad (4\text{-}1)$$

$$D50 = 0.0012\ V^3/(d)^{0.5} \qquad (4\text{-}2)$$

where

V = velocity, feet per second (The maximum velocity occurs near the crest where flow approaches critical depth)
d = Flow depth, feet, related to the above velocity
D50 = median stone size, feet
L = Length of protection, feet
H = Height of water above the weir, feet, at design velocity

NOTE: The minimum D50 shall be 6 inches.

Table 2-2 expands the D50 into a complete gradation. See chapter 2 also for information on thickness, filter, and installation.

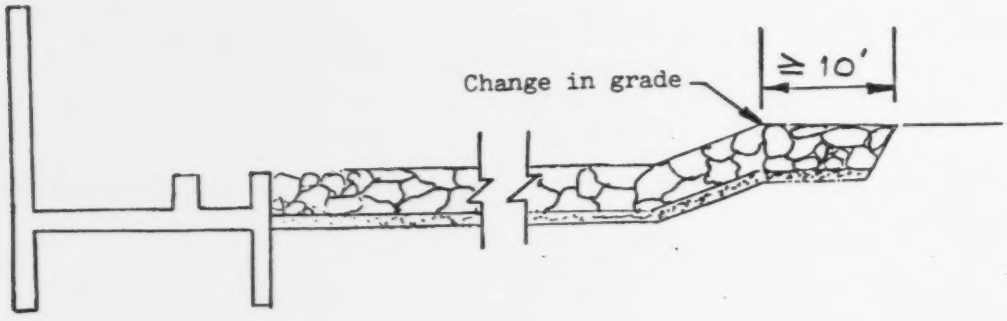


Figure 4-1. Diagram to Show Extending Riprap Beyond Change in Grade

D

DESIGN FORM D
CHANNEL PROTECTION UPSTREAM FROM A STRUCTURE
MINNESOTA TR-3

Reference: MN-TR-3, Chapter 4, Section A

Project: Sample Problem D County Rice

By SM²J Date 4/19/89 Ck'd By ~~AGS~~ Date 4/20/89

Velocity (V) 4.7 ft/sec Flow Depth (d) 3'

Height of Water over Weir (H) 2.9

A. (Eq'n 4-2) D50 = 0.012 V^3 /($d^{0.5}$) = 0.72' = 8½"

B. D50 must be greater than or equal to 6 inches

Use the larger D50 of those calculated in A and B above = 8½"

Length of Protection (L1) = 2 x H = 2 x 2.9 = 5.8' use 6' (Eq'n 4-1)

Riprap Gradation: (from Table 2-2)

D100	1.5 - 2.0 x D50	12¾" to 17"
D85	1.3 - 1.8 x D50	11" to 15¼"
D50	1.0 - 1.5 x D50	8½" to 12¾"
D15	0.3 - 0.5 x D50	2½" to 4¼"

Thickness of the Riprap Layer: 1.25 x $D100_{MAX}$ 1.25 x 17" = 21¼" (use 22"-24")

(See Chapter 2, Section E--minimum is 9-12 inch thickness)

Filter/Bedding Requirements: use SMN1 to design
Geotextiles may be considered also

B. OUTLET CHANNEL PROTECTION FOR STRUCTURES AND ENERGY DISSIPATERS

Most traditional grade and water control structures and energy dissipaters control turbulence and reduce discharge velocities within the confines of the structure. However, it is not possible to control all turbulence for the entire range of structure flows. Some turbulence or high velocities can still exist below these structures.

Flow downstream from these structures is considered moderately turbulent for the determination of minimum median stone size (D50). In cases where the discharge jet may occasionally fall beyond the end of the outlet structure, the flow is expected to be highly turbulent. The following procedure does not apply in such cases. This will require special design. Normally the stone size becomes prohibitively large for these special designs.

Riprap design downstream from impact basins is given in Technical Release No. 49.

Riprap below drop structures and other energy dissipating structures can be designed using the following procedures.

(1) Determine velocity and water depth at the structure end sill and apply equation (4-2). The D50 determined by equation (4-2) shall be icreased by 1.15 to allow for turbulence and water jet effects below the sill.

(2) Determine the minimum D50 size for the downstream channel based on the procedure for channel lining in Chapter 5.

(3) Use the larger stone size of the ones calculated for steps (1) and (2) above.

(4) The minimum thickness shall not be less than the end sill height.

(5) A bedding is required and filters as needed to control seepage and piping pressures. (See Chapter 2)

(6) Outlet channel protection should be placed to a distance downstream equal to 1.5 times the structure width but not less than 25 feet and to a minimum height equal to the discharge elevation in the structure.

(7) The riprap shall not end on a change of grade. Riprap should extend a minimum of 10 feet downstream from change in grade. See Figure 4-1.

(8) See Chapter 2 for information on gradation, filter, and installation.

E

DESIGN FORM E
OUTLET CHANNEL PROTECTION
FOR STRUCTURES AND ENERGY DISSIPATORS
MINNESOTA TR-3
Sheet 1 of 2

Reference: Minnesota Technical Release 3, Chapter 4, Section B

Project Sample Problem E County Carlton

By SM²J Date 3/24/89 Ck'd By ~~ABJ~~ Date 3/28/89

Structure Width (Sw) 24' Design Discharge (Q) 267 cfs

Elevation of Design discharge in channel (El) 947.2

Velocity (V) 8.3 ft/sec Depth in channel related to V (d) 3.1 ft

A. Eq'n 4-2: $D50 = 0.0012\ V^3/(d)^{0.5}$ = .39' = 4¾"

B. Use form to design channel lining and calculate D50 4"

C. Use the larger of the D50 values calculated in A and B above

D50 = 4¾"

D. Length of Protection (L1):

L1 = 1.5 x Sw = 1.5 * 24' = 36 ft

L1 must not be less than 25 feet; Riprap must be placed to elevation El or higher.

Riprap Gradation: (from Table 2-2)

D100	1.5 - 2.0 x D50	7" to 9½"
D85	1.3 - 1.8 x D50	6¼" to 8½"
D50	1.0 - 1.5 x D50	4¾" to 7"
D15	0.3 - 0.5 x D50	1½" to 2½"

Thickness of Riprap = 1.25 x D100(max) = 1.25 x 9½" = 12"

Bedding and Filter: Use Soil Mechanics Note #1 and Chapter 2 of MN TR-3.

Design Form F for Channel Lining Riprap
Sheet 2 of 2

Design Q = Channel Slope =

D50 guess	n value	b, bottom width	d, flow depth	z, side slope	b/d	P/R	D50	n value
1	2	3	4	5	6	7	8	9
5"	.034	24'	1.68'	3	14.3	24.7	3.8"	.033
4"	.033	24'	1.65'	3	14.5	24.8	3.8"	.033

Trapezoidal Channel:

$A = bd + zd$
$P = b + 2d\sqrt{1+z^2}$
$R = A/P$

Triangular Channel:

$A = zd$
$P = 2d\sqrt{1+z^2}$
$R = A/P$

Manning's Equation:

$V = (1.486/n)R^{2/3}S^{1/2}$
Continuity Equation
$Q = VA$

1. Select an initial D50 size to try.
2. Use Figure 5-2 to estimate an initial n value.
3. Determine bottom width and depth for this n value using Manning's equation, the design discharge, and the channel bed slope.
4. Select a side slope ratio, z.
5. Calculate b/d and record in column 6.
6. Use Figure 5-3 to determine P/R from b/d. Record in column 7.
7. Use Figure 5-4 or 5-5 to determine the D50 rock size.
8. Use Figure 5-2 to affirm that the n value is close to what was assumed.
9. If the n value is not approximately the same as what was assumed, repeat the procedure with different values.

Sample Problem E
Sheet 2 of 2
SMJ 3/24/89
3/24/89

CHAPTER 5. CHANNEL LINING

The procedure given below can be used for both subcritical and supercritical flow. For subcritical flow there is considerable experience and numerous published studies. For supercritical flow, however, there has been very little work done to establish similar guidelines because normally riprap has not been an economical solution due to the large rock sizes and volumes needed for protection against supercritical flows. The forces acting on the lining differ only in magnitude for uniform subcritical flows. However, between 0.85 dc and 1.1 dc (dc = critical depth) other forces such as surge, pulse, and negative forces come into play. Although these forces are known to exist, no reliable method of measuring or predicting them is currently available. Therefore, continuous flows in this range should be avoided if at all possible. Rock size required by Figures 5-4 and 5-5 shall be increased by a factor of 1.25 for the 0.85 dc to 1.1 dc range.

At the downstream end of the lining, a termination section as shown in Figure 2-5, Method B shall be used unless the lining abuts a structure or bedrock, in which case Method A in Figure 2-5 may be used. At the upstream end, the cross-section shall be as shown in Figure 2-5, Method B. If the upstream end abuts a structure or bedrock, Method A in Figure 2-5 may be used.

DESIGN PROCEDURES:

Trapezoidal Channels:

(1) Make an initial guess at the D50 rock size for the channel. Use Figure 5-2 to estimate Manning's n. Solve for depth d using Manning's equation. Figure 5-6 may be helpful for solving Manning's equation.

(2) Calculate the b/d ratio and enter Figure 5-3 to find the P/R ratio.

(3) Enter Figure 5-4 with Sb, Q, and P/R to find median riprap diameter (D50s) for a straight channel.

(4) Enter Figure 5-2 to find the actual n value corresponding to D50 from step 3. If the estimated and actual n values are not in reasonable agreement, another trial must be made.

(5) Determine corrections necessary for bends if this applies. See the section in Chapter 1 "Flow in Channel Bends" and design form H.

(6) Enter Figure 5-1 to determine the optimum stable side slope of the riprap surface. It is preferable to have the riprap at this side slope or a flatter one.

(7) See Chapter 2 to expand the gradation, design the filter, and for installation information.

Triangular Channels:

(1) Enter Figure 5-5 with Sb, Q, and Z. Find the median riprap diameter (D50) for straight channels.

(2) Enter Figure 5-2 to find the actual n value. If the estimated and actual n vales are not in reasonable agreement, another trial must be made.

(3) For channels with bends, see Chapter 1 under "Flow in Channel Bends". Design form H in Appendix A may be helpful also.

(4) Enter Figure 5-1 to determine optimum stable side slope of the riprap surface. It is preferable to have the side slopes at this ratio or flatter.

(5) See Chapter 2 for gradation design, filter design, and installation information.

Flow Resistance

The hydraulic analysis performed as part of the riprap design process requires the estimation of Manning's roughness coefficient. The base n value is largely a function of the material through which the channel is cut. For riprap lined channel, equations 5-1 through 5-3 are recommended. Equations 5-1 and 5-2 are based on laboratory and natural channel data (reference 13).

$$n = 0.093\ da^{0.167} \quad \text{for } 1.5 < da/D50 < 185 \qquad (5\text{-}1)$$

$$n = 0.019\ da^{0.167} \quad \text{for } 185 < da/D50 < 30{,}000 \qquad (5\text{-}2)$$

where,

n is the roughness coefficient for Manning's equation
da = average channel flow depth, feet
D50 = median bed size material, feet

The accuracy of equations 5-1 and 5-2 is dependent on having good estimates of median bed material size. On high gradient streams it is extremely difficult to obtain a good estimate of the median bed material size. For high gradient streams with slopes greater than 0.002 and bed material larger than 0.2 feet (gravel, cobble, or boulder size material), it is recommended that the relationship given in equation 5-3 be used to evaluate the base n (reference 13).

$$n = 0.39\ Sf^{0.38}R^{-0.16} \qquad (5\text{-}3)$$

where,

Sf = friction slope, ft/ft
R = hydraulic radius, feet

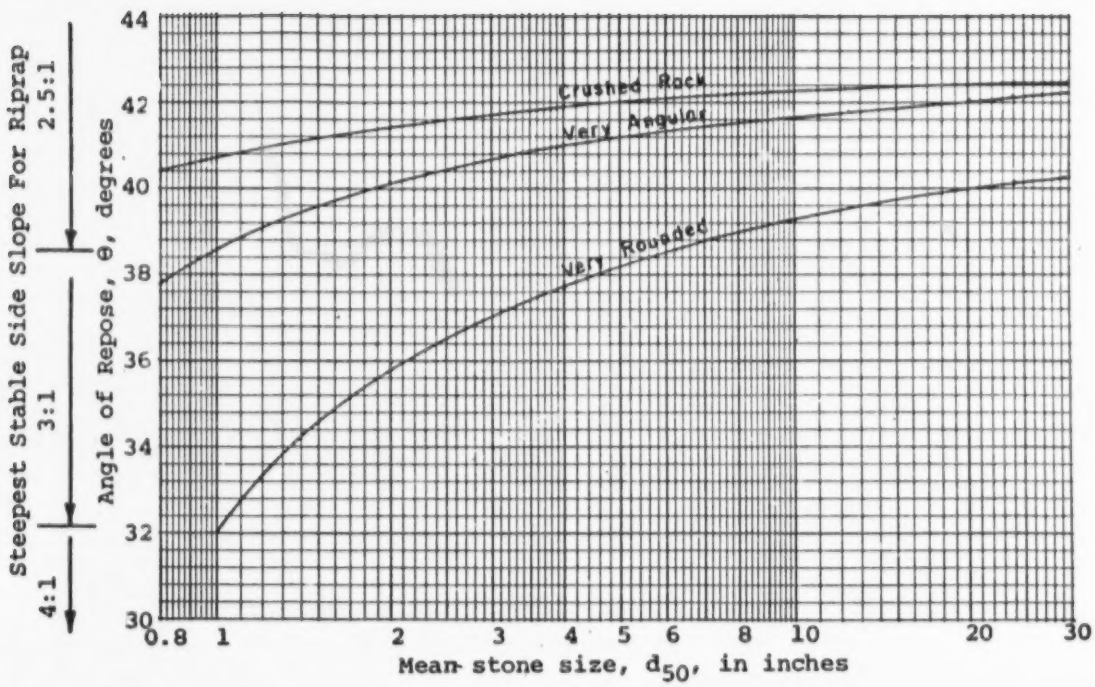


Figure 5-1. Optimum Riprap Side Slope for a Given Size Riprap

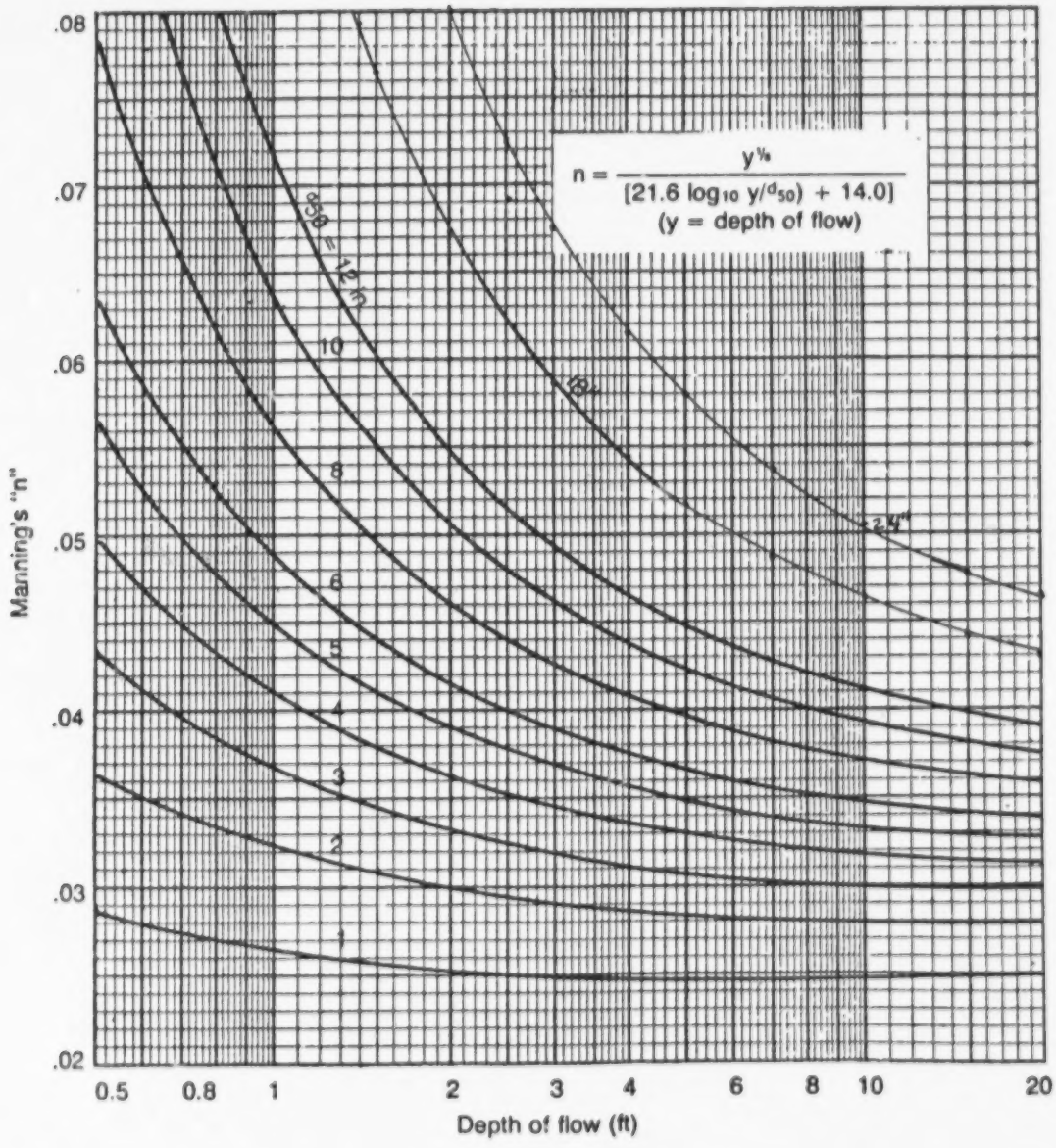


Figure 5-2. Values of n for riprap-lined channels
D50 size vs. depth of flow (d)

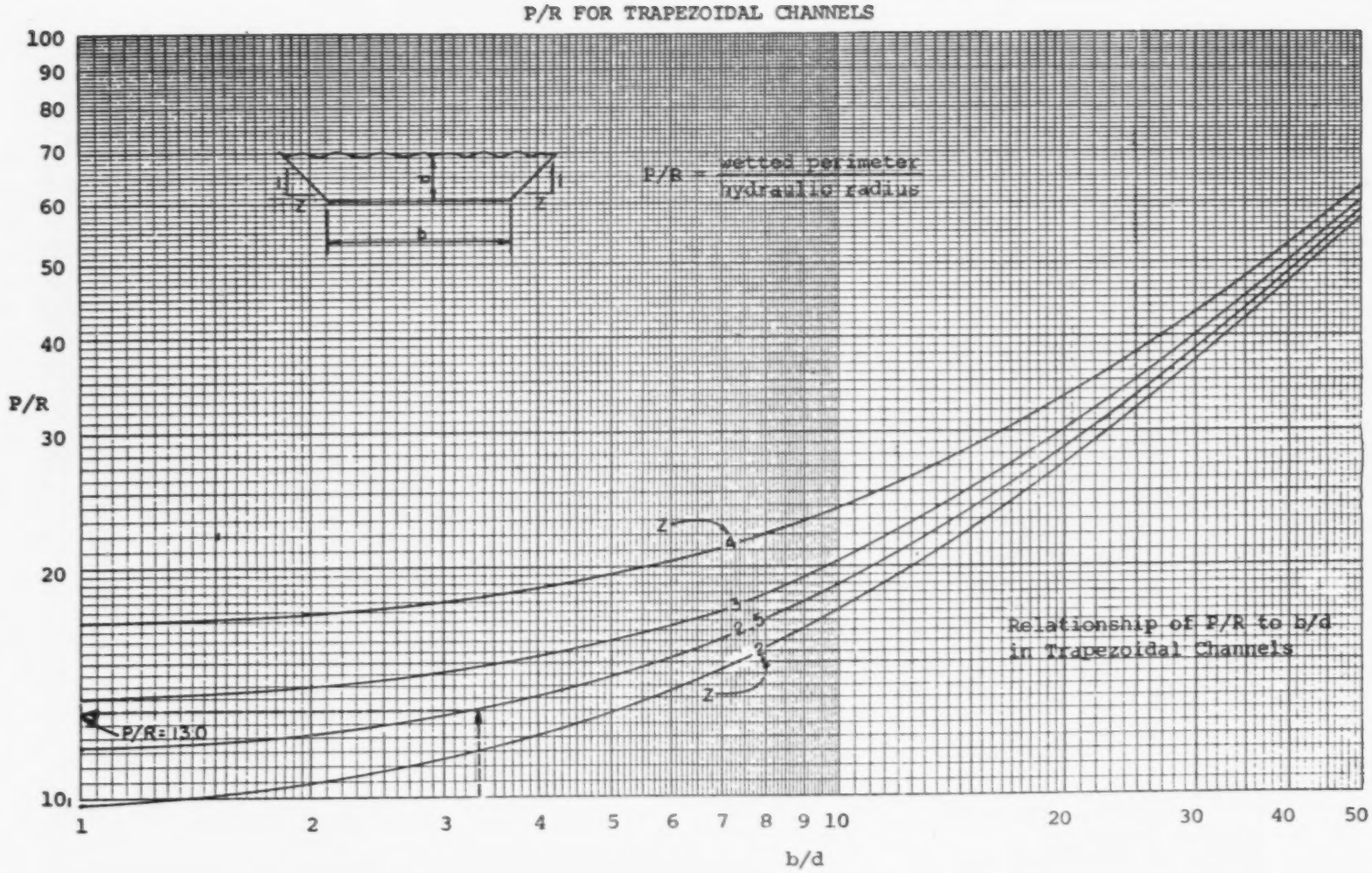


Figure 5-3. P/R For Trapezoidal Channels

Figure 5-4.

MEDIAN RIPRAP DIAMETER FOR STRAIGHT TRAPEZOIDAL CHANNELS

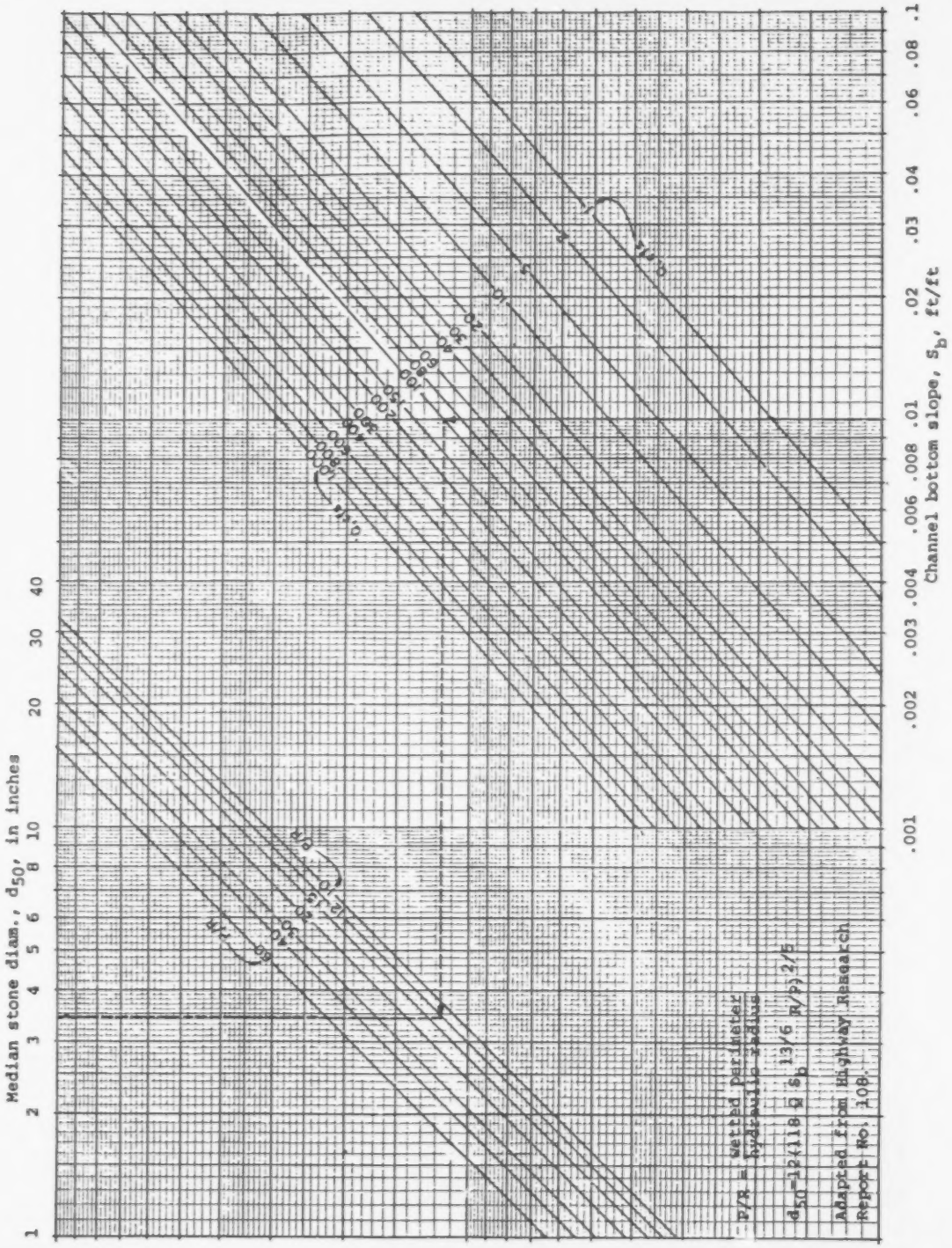
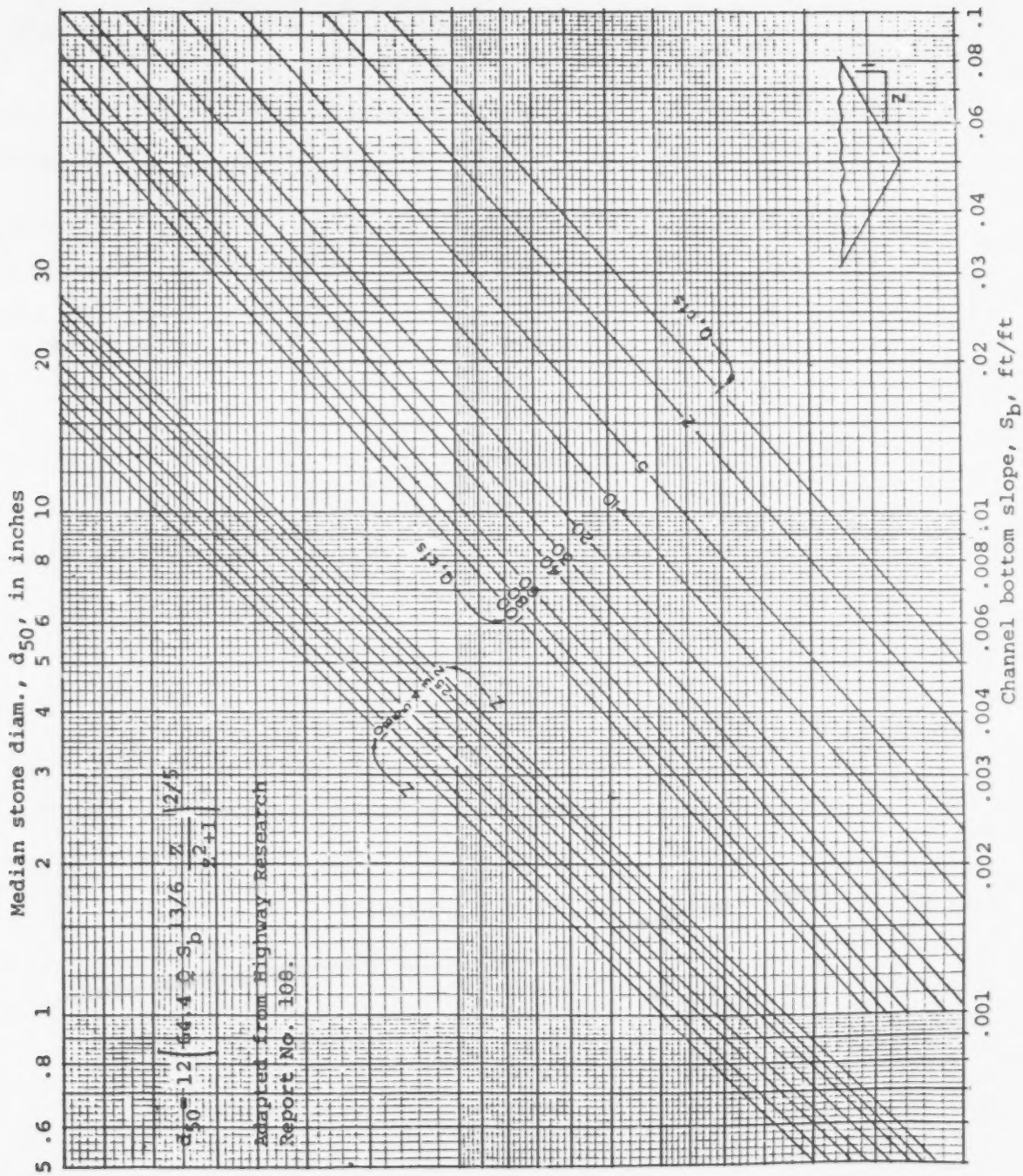


Figure 5-5.
MEDIAN RIPRAP DIAMETER FOR STRAIGHT TRIANGULAR CHANNELS



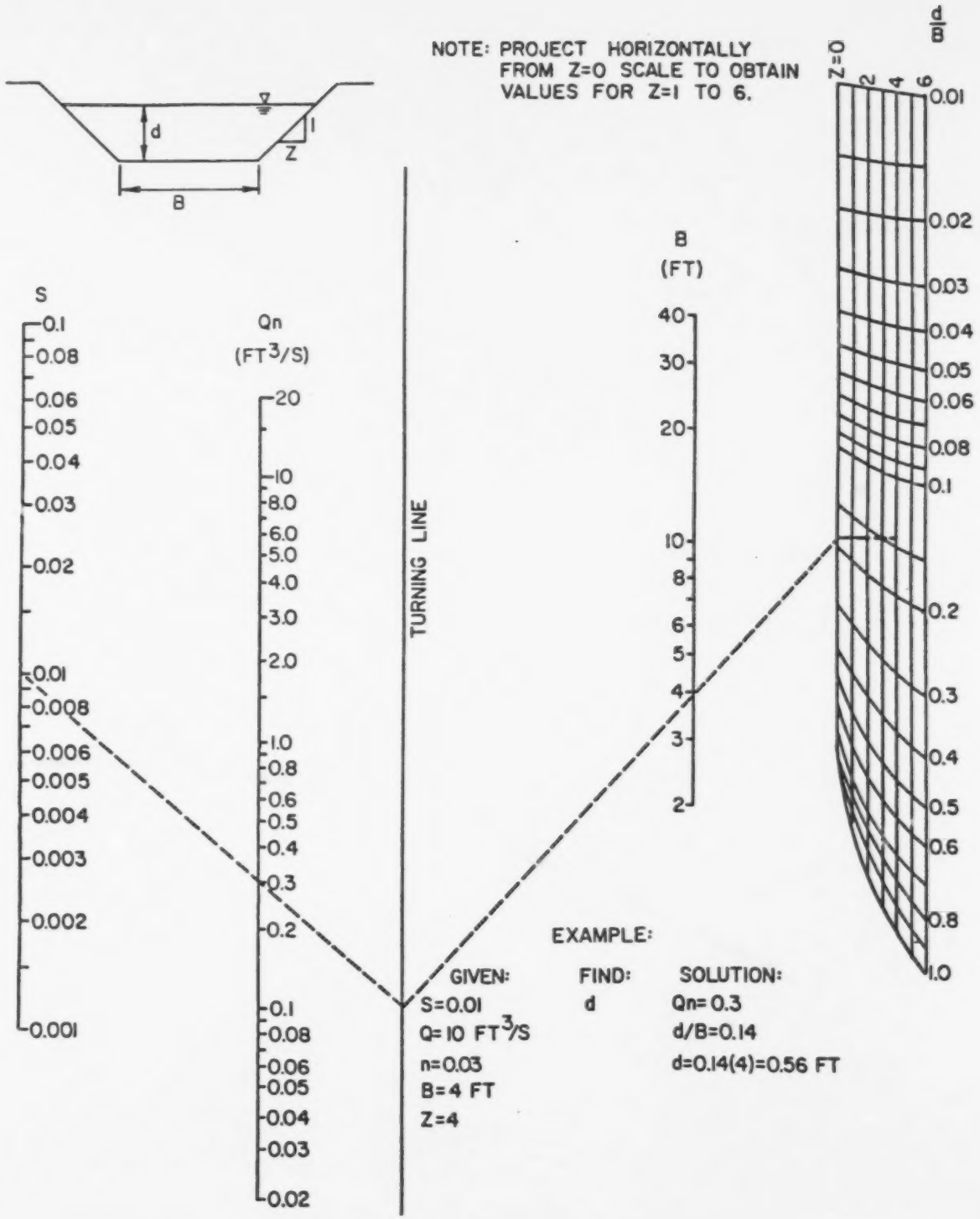


Figure 5-6. SOLUTION OF MANNING'S EQUATION FOR CHANNELS OF VARIOUS SIDE SLOPES.

F

DESIGN FORM F
CHANNEL LINING
MINNESOTA TECHNICAL RELEASE NO. 3
Sheet 1 of 2

Reference: Minnesota Technical Release 3, Chapter 5

Project Sample Problem F County Clay

By SM²J Date 3/23/89 Ck'd By ABS Date 3/24/89

Design Discharge (Q) 267 cfs Channel Bed Slope 0.01 ft/ft

Side Slope Ratio 3:1

☐ Triangular X-section ☒ Trapezoidal X-section

D50 selected: (sheet 2 of 2 for computations) 4"

Riprap Gradation: (from Table 2-2)

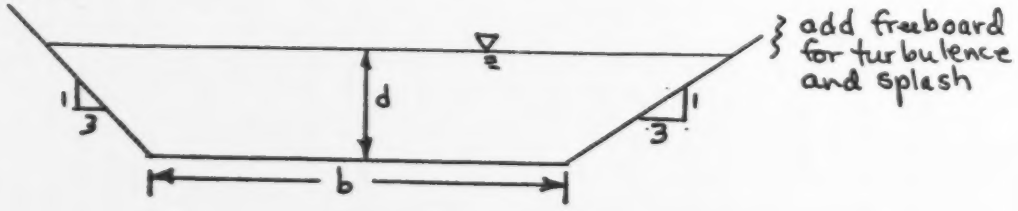
D100	1.5 - 2.0 x D50	6" to 8"
D85	1.3 - 1.8 x D50	5¼" to 7¼"
D50	1.0 - 1.5 x D50	4" to 6"
D15	0.3 - 0.5 x D50	1¼" to 2"

Thickness of Riprap Layer: $1.25 \times D100_{MAX}$ - $1.25 \times 8" = 10"$ (use 12")

(See Chapter 2, Section E--minimum thickness is 12 inches)

Bedding/Filter Design:
See SMN1

Design Sketch:



Design Form F for Channel Lining Riprap

Sheet 2 of 2

Design Q = 267 cfs Channel Slope = 0.01 ft/ft

D50 guess	n value	b, bottom width	d, flow depth	z, side slope	b/d	P/R	D50	n value
1	2	3	4	5	6	7	8	9
6"	.042	21.5	2.0	3	10.75	21.2	4"	.036
4"	.036	18'	2.0	3	9.0	19.6	5.4"	.040
5"	.039	20'	2.0	3	10.0	20.5	4.2"	.037
4½"	.038	19'	2.0	3	9.5	20.0	4.2"	.037 ← OK

Trapezoidal Channel:

$A = bd + zd^2$

$P = b + 2d\sqrt{1+z^2}$

$R = A/P$

Triangular Channel:

$A = zd^2$

$P = 2d\sqrt{1+z^2}$

$R = A/P$

Manning's Equation:

$V = (1.486/n)R^{2/3}S^{1/2}$

Continuity Equation

$Q = VA$

1. Select an initial D50 size to try.
2. Use Figure 5-2 to estimate an initial n value.
3. Determine bottom width and depth for this n value using Manning's equation, the design discharge, and the channel bed slope.
4. Select a side slope ratio, z.
5. Calculate b/d and record in column 6.
6. Use Figure 5-3 to determine P/R from b/d. Record in column 7.
7. Use Figure 5-4 or 5-5 to determine the D50 rock size.
8. Use Figure 5-2 to affirm that the n value is close to what was assumed.
9. If the n value is not approximately the same as what was assumed, repeat the procedure with different values.

Sample Problem F
SM²J 3/23/89 ABB 3/24/89

CHAPTER 6. STREAMBANK PROTECTION

Streambank protection differs from channel lining in that normally only the banks are furnished with protective layers and the bottom materials vary across the section. This results in a different stress distribution on the protection face than determined for channel lining. The maximum stresses are highly dependent on the relative roughness and velocity distribution between sections with different bottom materials.

The ends and toe of the riprap protection must be protected from undercutting or an allowance made for the toe or end to flex for minor undercutting. Figures 2-5 and 2-6 illustrate toe and end protection.

The toe protection is dependent on the type of construction. For dry construction either Method A or B (Figure 2-5) is satisfactory. If construction has to be done in or under water, placement control is difficult and hard to verify. To compensate for construction in water deeper than 3 feet, the thickness should be increased by 50% in the toe section.

End protection is needed if the rock is terminated at a point that is not known to be stable. If the rock is terminated at a stable point such as structure, a section of rock, or where flow and shear forces are parallel to the bank, etc., Method A (Figure 2-5) may be used. In most cases, some question will exist as to the stability of the end section; therefore Method B (Figure 2-5) should be used.

Stabilizing Both Banks

In some situations, both banks may be eroding but the bottom appears to be stable. Initially, the design can be calculated using the chapter on streambank protection. However, if the toes appear to extend over a significant portion of the channel bottom, the designer should consider full channel lining. It would not be wise to leave a narrow band of bare earth that may be eroded since it is the weak point across the cross-section.

Extent of Protection

The longitudinal extent of protection required for a particular bank stabilization measure is highly dependent on local site conditions. In general, the revetment should be continuous for a distance greater than the length that is impacted by channel flow forces severe enough to cause dislodging and/or transport of bank material. Although this is a vague criteria, it demands serious consideration. Review of existing bank protection sites has revealed that a common misconception in streambank protection is to provide protection too far upstream and not far enough downstream (reference 13).

Toe Depth

The undermining of revetment toe protection has been identified as one of the primary mechanisms of riprap revetment failure, especially where riprap is used for streambank protection. Estimates of the depth of scour are needed so that the protective layer is placed sufficiently low in the streambed to prevent

undermining. The relationships presented in equations 6-1 and 6-2 can be used to estimate the probable maximum depth of scour due to natural scour and fill in straight channels and in channels having mild bends. These equations are based on data presented by Blodgett (reference 13). In application, the depth of scour, ds, determined from equation 6-1 or 6-2, should be measured from the lowest elevation in the cross section. It is assumed that the low point in the cross section may eventually move adjacent to the riprap (even if this is not the case in the current survey).

$$ds = 12 \text{ feet} \quad \text{for } D50 < 0.005 \text{ feet} \qquad (6\text{-}1)$$

$$ds = 6.5D50^{-0.11} \quad \text{for } D50 > 0.005 \text{ feet} \qquad (6\text{-}2)$$

where,

ds = estimated probable maximum depth of scour, feet

D50 = median diameter of bed material, feet

Design Procedure

State-of-the art streambank protection design uses tractive stress procedures to select the size of the rock riprap. The primary references are #3 and #29 as listed in the bibliography. The design procedure given here may be better understood after reading NNTC Design Note #4 (Reference 29).

1. Determine s_e (energy slope) and r (hydraulic radius) for the flow conditions being analyzed.

2. Compute the Manning's n for the selected rock riprap using the following (d50 in feet). Choose the appropriate condition.

   For shallow depths, d = flow depth, (from practice standard 468)

   $$n = d^{1/6}/\{21.6 \log (d/D50) + 14\} \qquad (6\text{-}3)$$

   For greater flow depths, (from TR-59)

   $$n = 0.0395\ d50^{1/6} \qquad (6\text{-}4)$$

3. Compute the reference tractive stress using equation 6-5.

   $$T_r = gw\ r\ s_e \qquad (6\text{-}5)$$

   where

   gw = unit weight of water, lbs/ft^3
   r = flow depth in feet
   s_e = energy slope, feet/foot
   T_r = reference tractive stress, lbs/ft^2

4. Use Figures 6-1 and 6-2 to obtain C_{Tb} and C_{Ts}. Multiply the reference tractive stress calculated in step 3 by these factors to determine the maximum stress on the bottom and sides, respectively.

5. Use Figure 2-3 (taken from TR-59, Supplement 1) to obtain an estimated angle of repose, , for the size and shape of riprap selected.

6. Use calculated above and the side slope ratio to calculate K (coefficient modifying the tractive force for gravitational forces on coarse, non-cohesive materials on channel sides) using equation 6-6 below.

$$K = \{1- \{(\sin^2 (\cot^{-1} z))/\sin^2 \Theta \}\}^{1/2} \qquad (6\text{-}6)$$

where,

z = side slope ratio

Table 6-1. For Use with Equation 6-6.

z	$\cot^{-1} z$	$\sin^2 (\cot^{-1} z)$
1.5	$33^{\circ}41'$	0.3076
2.0	$26^{\circ}31'$	0.1993
3.0	$18^{\circ}25'$	0.0998
4.0	$14^{\circ}02'$	0.0588

7. Compute the allowable tractive stress using equation 6-7. Use FS $\geq$ 1.0.

$$Tsa = K\ C50\ D50 / FS \qquad (6\text{-}7)$$

where,
Tsa = allowable tractive stress, lbs/ft^2
C50 = 4.0
D50 = median rock size, feet
FS = desired factor of safety

8. Compare the allowable tractive stress calculated in equation 6-7 to the maximum tractive stresses on the bottom and sides determined in step 4.

9. If the allowable value is less than the computed maximum(s), increase the size of the rock riprap and repeat the analysis until a stable rock riprap size is determined. Design form G in Appendix A is available for documentation.

10. If the protection is to be on a curve, the examples in Reference 29 are very helpful. The maximum tractive stress within a curve is found "at the break in grade between the bed and banks." Therefore the maximum tractive stress within the curve acts on both the channel bottom and side slopes.

11. From the curve data, obtain r_c = radius of curvature in feet. Compute the top width of the water surface in feet (w) for the flow being analyzed. With these values, compute the ratio w/r_c.

12. Using the above w/r_c and Manning's n, enter Figure 6-3 to obtain a Tc/T ratio. Compute $Tc \triangleq Tc/T \times T$ = maximum stress within the curve. This value should be compared to the maximum tractive stresses within a straight channel. In no case should the stress within the curve be less than the stresses on either the sides or bottom of a straight channel.

13. Compare Tc to that computed in step 7. If the allowable tractive stress is less than the maximum tractive stress in the curve (Tc), increase the rock size and repeat the analysis.

14. See Chapter 2 for information on riprap gradation, filters, and layer thickness.

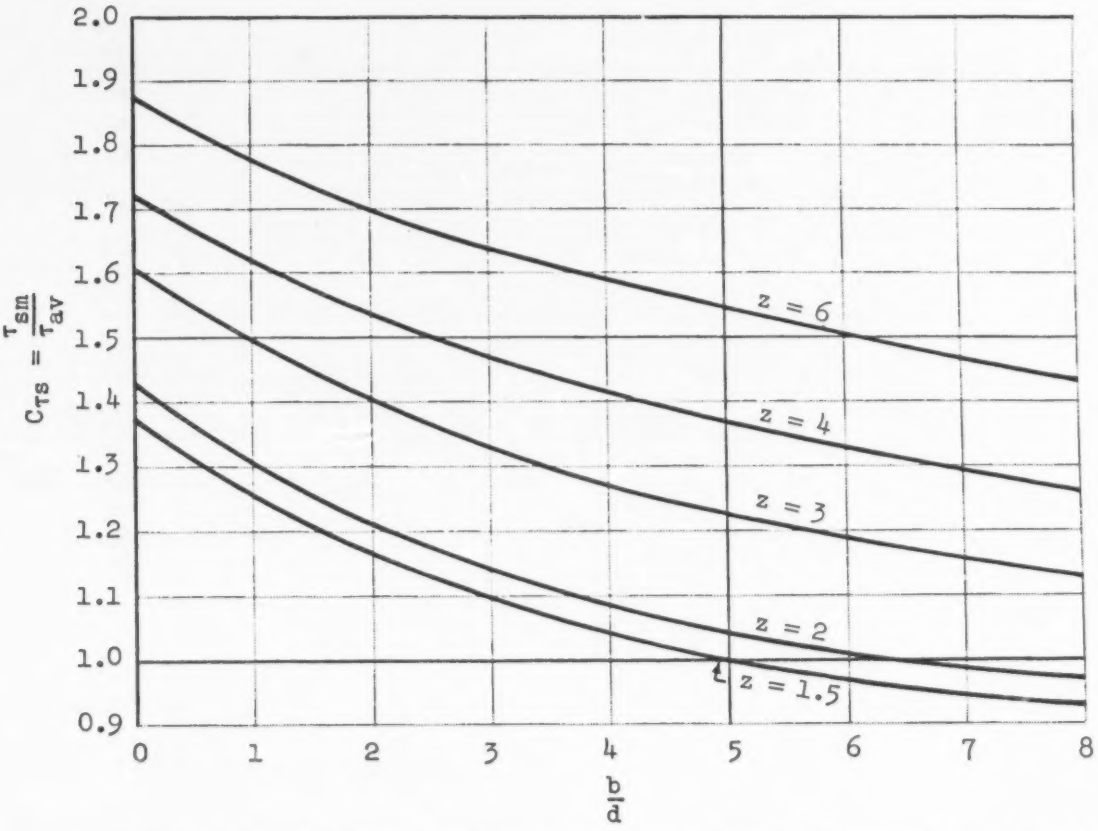


Figure 6-1. Maximum tractive stress on sides of trapezoidal channels

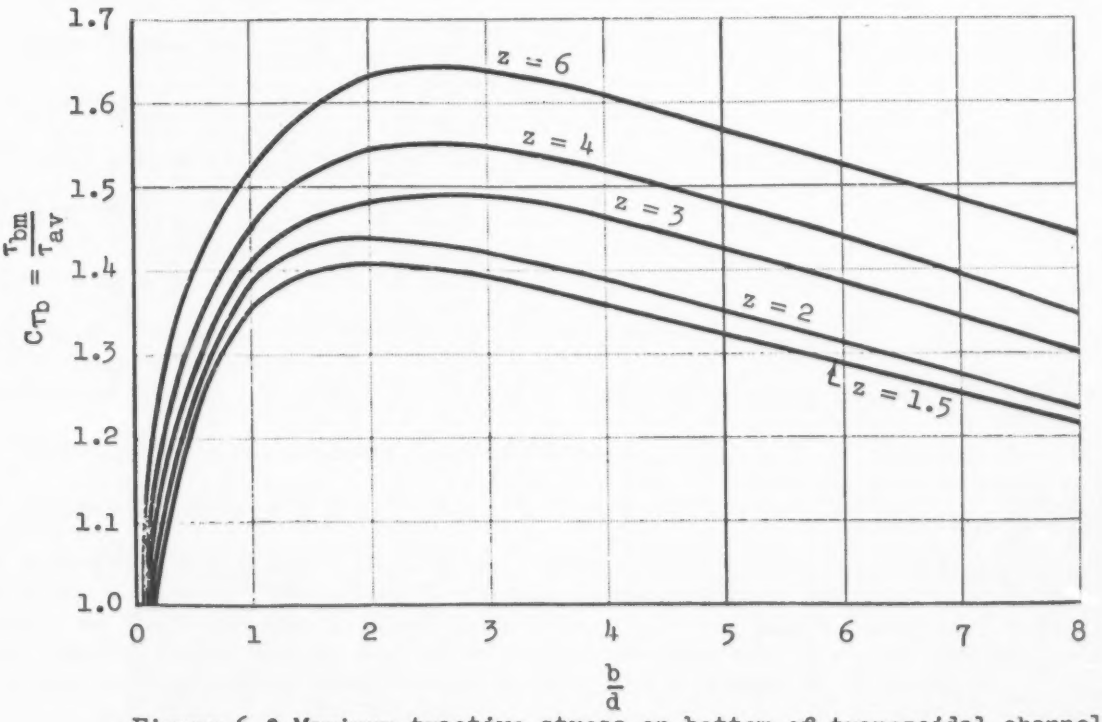


Figure 6-2 Maximum tractive stress on bottom of trapezoidal channels

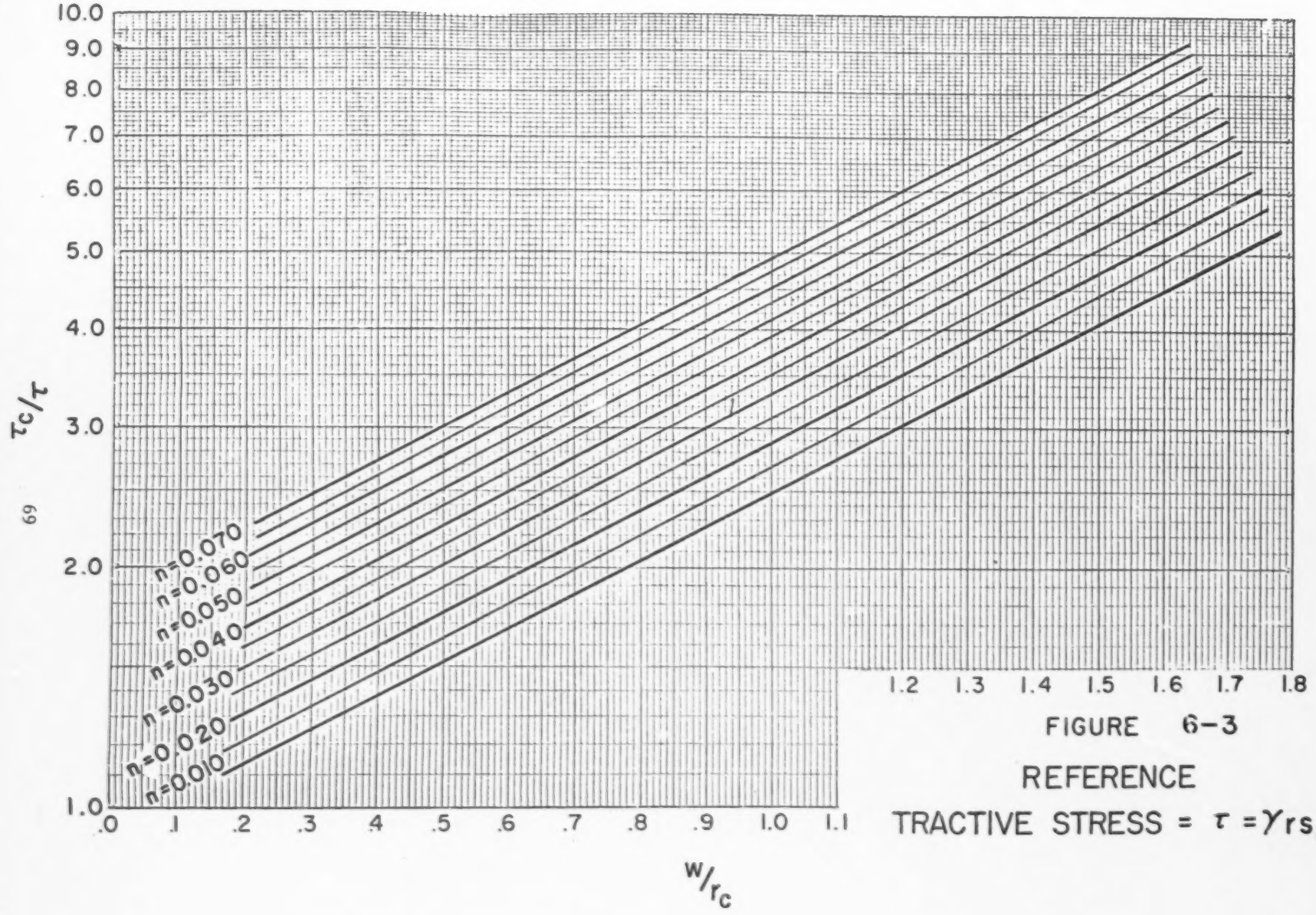


FIGURE 6-3

REFERENCE

TRACTIVE STRESS = $\tau = \gamma r s_e$

G

DESIGN FORM G
STREAMBANK PROTECTION
MINNESOTA TECHNICAL RELEASE NO. 3

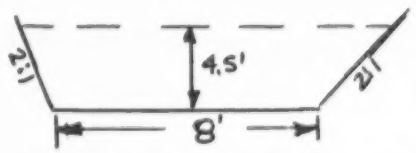
Reference: Minnesota Technical Release No. 3, Chapter 6 and NNTC DN #4

Project Sample Problem G County Wabasha

By SM²J Date 12/1/88 Ck'd By ~~ABS~~ Date 12/2/88

1. Side Slope Ratio (z) 2 Cross-sectional Area (A) 76.5 ft²

Sketch of cross-section:



(Not to scale)

2. Perimeter (p) 28.1 feet Hydraulic Radius (r) 2.72 feet

3. Energy Slope (Se) 0.0032 ft/ft (from WSP2)

4. Reference Tractive Stress: T_r = gw r s_e = 62.4 #/ft² x 2.72 x .0032 = 0.543 psf (eq'n 6-5)

5. Bottom width (b) 8 feet Depth of flow (d) 4.5 b/d 1.78

6. C_{Ts} (Figure 6-1) 1.23 Max. Side Stress (Ts = T_r x C_{Ts}) 0.668 psf

7. C_{Tb} (Figure 6-2) 1.44 Max. Bottom Stress (Tb = T_r x C_{Tb}) 0.782 psf

ROCK SIZE TO TRY: 6" (9")

8. Mannning's n: (Eq'n 6-3 or 6-4) .0371 (.0417)

$n = d^{1/6} / (21.6 \log (d/D50) + 14)$ or $n = .0395\ D50^{1/6}$

9. Angle of Repose (θ) 41.3° K = $(1 - ((\sin^2 (\cot^{-1} z))/\sin^2\theta))^{1/2}$ .7365

10. Factor of Safety (FS)(use 1.0 initially) 1.0

11. Allowable Tractive Stress = Tsa = K x 4.0 x D50 /FS = 1.47 (2.21)

In a straight reach compare the value in step 11 to the larger of the two values from steps 6 and 7. The allowable tractive stress must be greater than the maximum stresses on the sides and bottom. Otherwise, choose a larger riprap and repeat the design analysis. If Tsa is much greater than the maximum stresses, you may wish to try a smaller rock size. Continue with step 12 for riprap on a curve.

Actual Safety Factor: Tsa/(Tb or Ts, whichever is larger) = $\frac{1.47}{.782} = 1.88$

$\left[\frac{2.21}{.782} = 2.83\right]$

12. Radius of Curve (r_c) 37.8 feet Top Width (w) 35.6 feet

w/r_c = 0.94

13. (Figure 6-3) Tc/T = 3.4 (3.6) Maximum stress in curve Tc = T_r x Tc/T 1.846 / (1.955)
maximum stress exceeds allowable for 6" – try 9" D50
In a curved reach, compare the value at the end of line 13 with those in lines 6 and 7. Line 13 must be larger or an error is likely. Then compare line 13 to line 11. The value in line 11 must be larger or a different size riprap should be chosen. The design procedure must be repeated.

Actual Safety Factor: Tsa/Tc = 2.21 / 1.955 = 1.13 ok

14. Distance upstream of Pc to protect: Lu = 0.4 w = 0.4 x 35.6

(Eq'n 1-2) Lu = 14.24' use 15' feet

15. Distance downstream of Pt to protect (eq'n 1-3) = .4635 $r^{1/6}$ d / n =

.4635 x 1.1815 x 4.5 / 0.0417 = 59.1 feet (use 60')

16. Avg. Velocity 3.92 ft/sec g = 32.2 ft/sec^2

17. (Eq'n 1-1) z = 1.5 $((Va^2w)/gr_c)$ = 0.68' feet

Increase the riprap protection elevation by this amount, z, to account for superelevation of the flow due to the curve.

18. Toe Protection: Method A ___ or Method B X

19. Riprap Gradation:

D100	1.5 - 2.0 x D50	13½" to 18"
D85	1.3 - 1.8 x D50	11¾" to 16¼"
D50	1.0 - 1.5 x D50	9" to 13½"
D15	0.3 - 0.5 x D50	3" to 4½"

20. Thickness of Riprap Layer: 1.25 x $D100_{Max}$ = 1.25 * 18" = 22½" (use 24")

minimum thickness is 12 inches

Filter/Bedding: geotextile will be used

DESIGN FORM H
RIPRAP FOR FLOW IN CHANNEL BENDS
MINNESOTA TECHNICAL RELEASE NO. 3

Reference: Minnesota Technical Release No. 3, Chapter 1, Section E

Project Sample Problem H County Wabasha

By SM²J Date 12/1/88 Ck'd By ~~ABF~~ Date 12/2/88

Top Width (w) 35.6 feet Avg. Velocity (Va) 3.92 ft/sec

$g = 32.2$ ft/sec^2 Radius of Bend (r_c) 37.8 feet

(Eq'n 1-1) $z = 1.5\ ((Va^2 w)/g r_c) =$ 0.68 feet

Increase riprap protection elevation by this amount, z, to account for superelevation due to the bend.

Hydraulic radius (r) 2.72 feet Flow Depth (d) 4.5' feet

Manning's n 0.0417

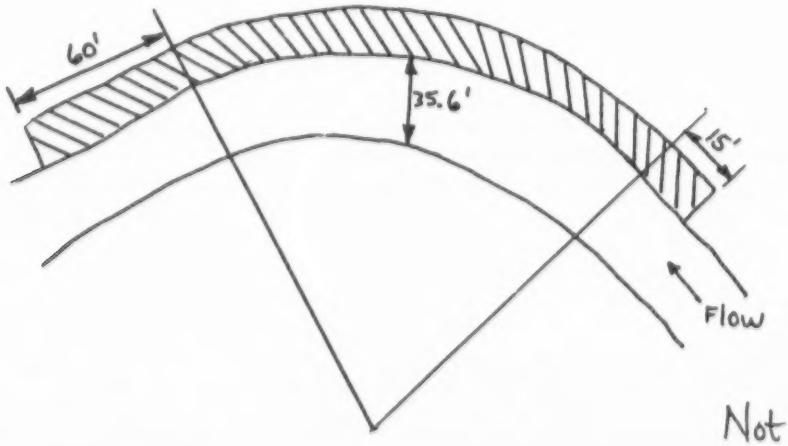
EXTENT OF RIPRAP: (Reference MN TR-3, Chapter 1)

See Figure 1-6 for layout. Compute upstream and downstream distances below.

(Eq'n 1-2) $Lu = 0.4\ w = 0.4 \times$ 35.6 = 14.24'-use 15 feet

(Eq'n 1-3) $Ld = (0.4635\ r^{0.1667} d)/n =$ 59.1 - use 60 feet

Design Sketch: (or attach drawing)



Not to scale

CHAPTER 7. TIPS FOR FIELD EVALUATION OF RIPRAP

A designer has carefully chosen the proper riprap gradation for the installation. Now the field engineer must ascertain that the rock installed meets the criteria. This chapter gives tips and procedures to help the field engineer do the job.

A. Perimeter Measurement Procedure

Riprap gradations are based on the weight and shape of a particle. The particles may be spherical, cubical, or something between those two shapes. Weight is the critical factor for the stability of the individual rock particles. Weighing rocks is not practical above about 100 lbs. Visual observation is not a reliable method for determining a rock's weight. Therefore, an equivalent dimension is often specified as the gradation parameter.

Visual observation is not an acceptable way to determine an equivalent "d" or rock gradation. Once a representative proper gradation has been determined by physically measuring or weighing the rock particles, visual observation may be used as a construction inspection tool. Visual observation of the complete rock layer (not just the surface) should approximate the appearance of the "proper gradation sample". Apparent variations in the visual observation will usually require physically measuring or weighing another sample area.

A procedure to estimate the weight and equivalent dimension "d" of a rock requires measuring the major and minor circumferences or perimeters of the rock in feet. See Figures 7-1 and 7-2 for examples of measuring the rock. The sum of the two perimeters is used to (1) graphically read the rock weight in pounds and equivalent dimension in inches from Figure 7-3 or (2) calculate the rock weight and equivalent "d" by using equations 7-2 and 7-3.

The perimeter measurement method provides an approximation of the rock weight. It appears to provide a more accurate weight than obtained by measuring actual dimensions. An error of one inch while measuring the "d" of a 12 inch rock can yield a 25% error in theoretical weight. Averaging the "d's" of oblong shaped rocks can also produce significant error.

The perimeter measurement method can produce an error of approximately $\pm 10\%$ when compared to actual (scale) weights. The W and d lines on Figure 7-3 are based on the average of a perfect sphere and a perfect cube. The perimeter measurement compensates for other than "perfect" shapes. The error is usually negligible in practical applications. The last page of this chapter has the derivation of the equations.

Precautions.

1. Figure 7-3 and equations 7-2 and 7-3 are for rock that has a specific gravity of 2.65 (165 lbs/ft3). Use this graph or formulas unless the actual specific gravity (Gsa) is known and varies more than 5 percent (± 0.13). To correct to the actual weight (Wa) use equation 7-1.

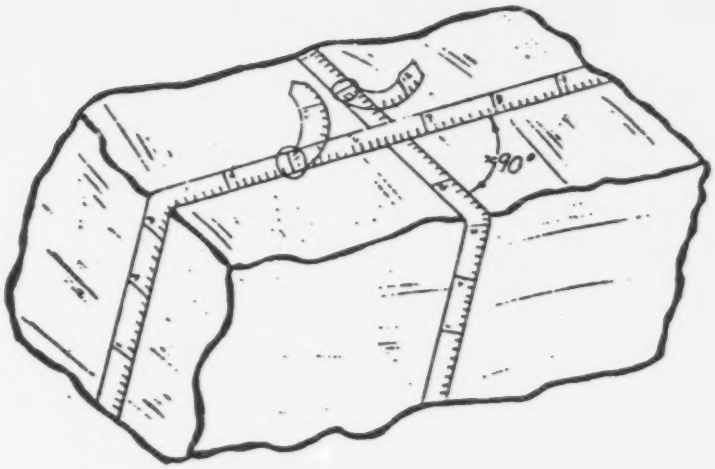


Figure 7-1. Measurement of P1 and P2 on blocky rock

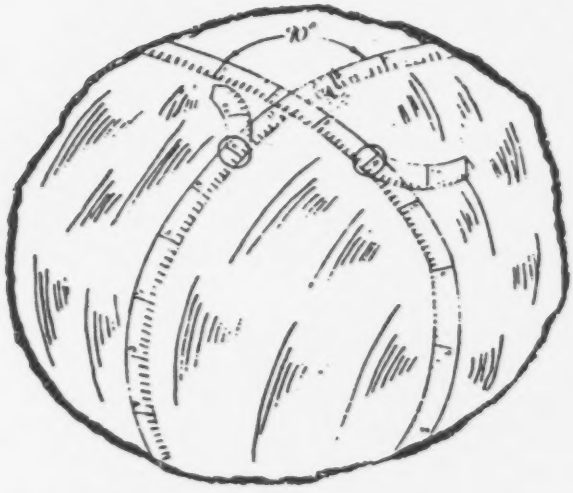
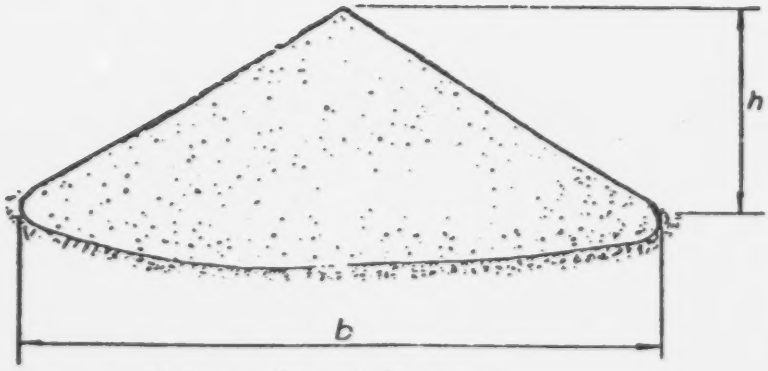


Figure 7-2. Measurement of P1 and P2 on spherical rock



$$\text{Volume } (ft^3) = \frac{.314 \times b^3 \times h}{12}$$

(b, and h in feet)

Figure 7-4. Volume of a cone for approximate volume of small rock when checking gradation

$$Wa = W/2.65 \times Gsa \qquad (7\text{-}1)$$

where,

W = weight of rock from Figure 7-3 in lbs.

Wa = actual weight of rock, converted for density other than 165 lbs/ft^3 (Gsa = 2.65)

Gsa = actual specific gravity (dimensionless)

2. When measuring the major and minor perimeters, do not measure sharp peaks, protrusions, or valleys. Move the tape slightly off the 90 degree angle or adjust the measurement to represent the rock's general shape.

3. Equation 7-2 identifies an approximate relationship of the weight of the rock to the sum of the two measured perimeters. Use the procedure below for the perimeter measurement method. Use equation 7-3 to determine the equivalent "d".

$$(P1 + P2)^3 / 3 = W* \qquad (7\text{-}2)$$

$$d = 1.68\ (P1 + P2) \qquad (7\text{-}3)$$

where,

P1 = major perimeter measurement, feet
P2 = minor perimeter measurement, feet
W* = approximate weight, lbs.
d = approximate equivalent dimension, inches

Procedure for Perimeter Measurement Method

1. Lay the rock in its most probable laying position.

2. Imagine two vertical cutting planes passing through the rock at nearly right angles to each other. See Figures 7-1 and 7-2 for illustrations. Measure the two resulting perimeters in feet and add them together. These measurements are P1 and P2 for equation 7-2.

3. Enter Figure 7-3 at (P1+P2) and move horizontally to the intersection with the W line,(Lower line). Follow down the chart and read the approximate weight in pounds on the bottom scale.

4. To determine the equivalent dimension, d, enter Figure 7-3 with the weight at the bottom of the chart, proceed vertically to the d line, and move horizontally to the right to read the size in inches. The size can also be read by entering Figure 7-3 with (P1+P2), moving horizontally to the W line,

moving vertically to the d line, and then horizontally to the right hand scale. Note the example given on Figure 7-3.

5. To determine the weight of small rock and sand/gravel, determine the volume in cubic feet and multiply by 100 lbs. Figure 7-4 illustrates this for a cone-shaped pile. However, a bucket of known volume (such as 5 gallon) can be used also.

After the weight and equivalent dimension "d" of each rock (except small rock, gravel) are determined, they need to be accumulated into size ranges that are larger than the particular rock size such as 1.5D50, D50, etc. The weights of the rocks that have a "d" greater than the designated size are accumulated and considered larger than that rock size. The cumulative percentage is subtracted from 100 percent to obtain the percent smaller. Example 1 may help clarify this concept.

Short Cut Procedure

1-2. Follow the steps as described above for "Procedure for Perimeter Measurement Method".

3. The chart can be approximated by the equation 7-4. (This is the same as equation 7-2 but has the terms rearranged.)

$$W* = 1/3\ (P1+P2)^3 \qquad (7\text{-}4)$$

4-5. Same as steps 4 and 5 above.

The short cut procedure is an approximation. It can be derived mathematically when one considers a perfect sphere and a perfect cube. Most riprap is actually between these two shapes. Mathematically, the weight of a perfect cube and a perfect sphere (assuming a specific gravity of 2.65) are as given below. The last page of this chapter contains the derivation of these equations.

Perfect Cube $W = 0.323(P1+P2)^3$ (7-5)

Perfect Sphere $W = 0.349(P1+P2)^3$ (7-6)

These equations are approximately equal to Equation (7-4) above.

This method is offered to aid individuals in determining whether the riprap is the size specified. It is not always convenient to carry a chart that converts approximate dimensions to weights.

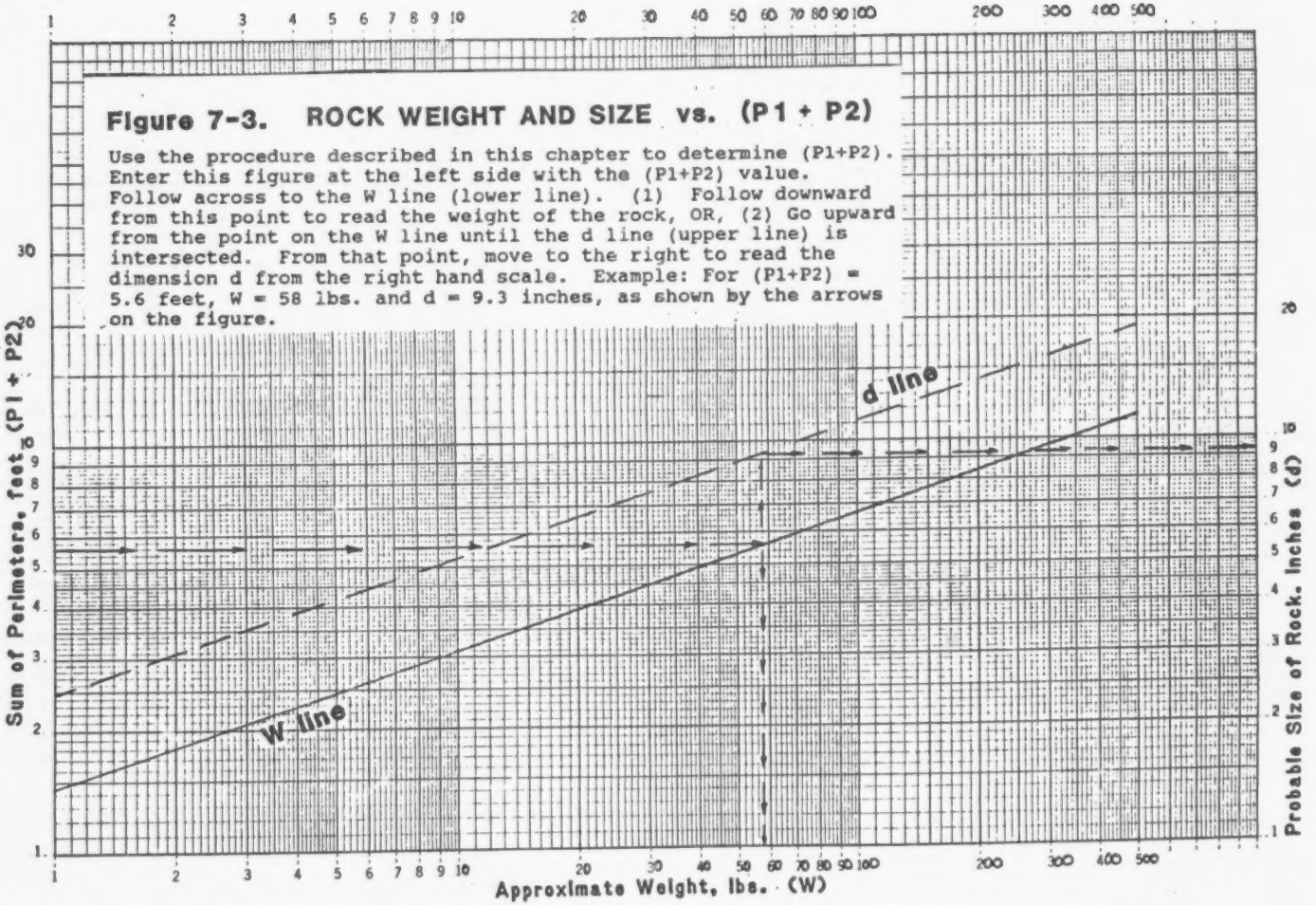


Figure 7-3. ROCK WEIGHT AND SIZE vs. (P1 + P2)

Use the procedure described in this chapter to determine (P1+P2). Enter this figure at the left side with the (P1+P2) value. Follow across to the W line (lower line). (1) Follow downward from this point to read the weight of the rock, OR, (2) Go upward from the point on the W line until the d line (upper line) is intersected. From that point, move to the right to read the dimension d from the right hand scale. Example: For (P1+P2) = 5.6 feet, W = 58 lbs. and d = 9.3 inches, as shown by the arrows on the figure.

B. Sample Gradations

When checking a gradation, it is helpful to have the contractor fabricate a section with the correct gradation so it can be visualized by the inspector and the contractor. The example below provides information on doing this. The rock and filter gradations should be ready before placement. Mixing them as they are placed is NOT acceptable.

Fabrication of a Field Sample.

At times it is helpful to fabricate a riprap sample and lay it in a measured area to visualize what a gradation should look like in place. The example below demonstrates how this might be done. In choosing the size of sample to fabricate, it is suggested that it be at least 50 times the median rock weight, W50, or 10 times the maximum rock weight, W100, whichever gives the larger total sample weight.

It is further suggested that if the lower end of the riprap sample is small rock, it is helpful to insert a 30% (W30) point, taken from the gradation curve, between the W50 and W15 points when creating the sample. The size gap between the W50 and the W15 can be large. Adding this extra point breaks the sample into two parts that are easier to pick out than is the one that must cover such a broad range. This has been done in this example.

Wmax = 116 lbs.
W85 = 82 lbs.
W50 = 20 lbs.
W30 = 2.5 lbs.
W15 = 0.6 lbs.
Wmin = 0.1 lbs.
(Gradation given in specification.)

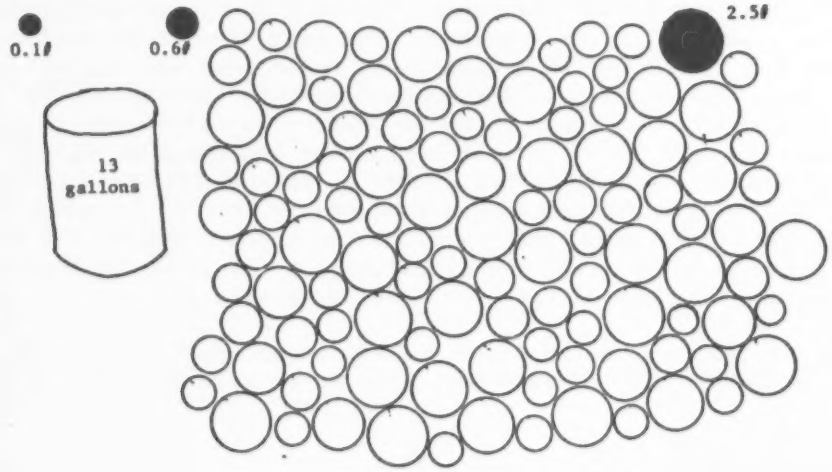
Figure 7-7. Sample calculations for riprap sample

Gradation %	Wt.	% of Sample	Weight to make 1160# sample	Avg. Rock Weight	Number of Rocks
Wmax	116#				
		100-85=15%	.15 x 1160#=174#	(116+82)/2=99#	174/99= 2
W85	82#				
		85-50=35%	.35 x 1160#=406#	(82+20)/2=51#	406/51= 8
W50	20#				
		50-30=20%	.20 x 1160#=232#	(20+2.5)/2 = 11.25#	232/11.25 = 21
W30	2.5#				
		30-15=15%	.15 x 1160#=174#	(2.5+0.6)/2= 1.55#	174/1.55 = 112
W15	0.6#				
		15-0 =15%	.15 x 1160#=174#	(.6+.1)/2 =.35#	174/.35 = 497 *
Wmin	0.1#				

For sample size: W100 = 116# 10 x 116 = 1160# OR W50 = 20#
and 50 x W50 = 50 x 20# = 1000# (use larger)

* Not realistic to count; measure 1.74 cubic feet or 13 gallons of rock that is 1" to 2" size.

Figure 7-5. "Key" rocks for riprap sample



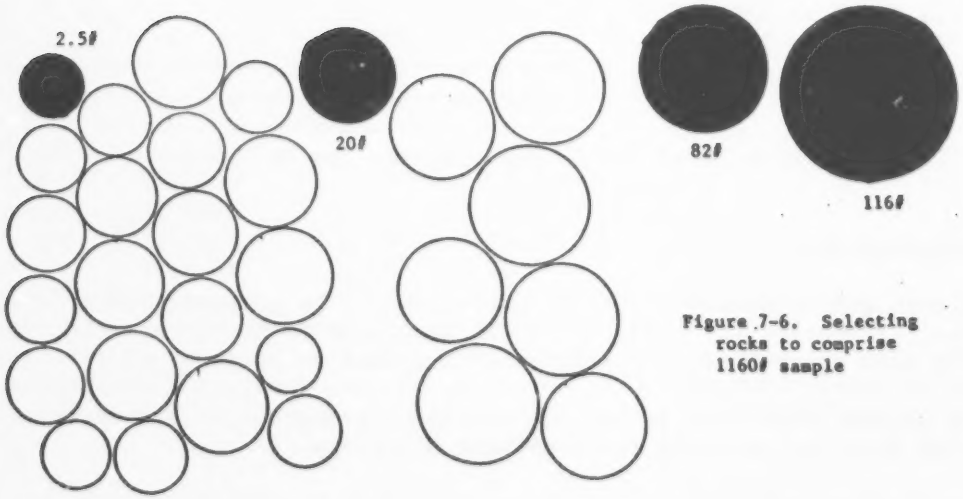


Figure 7-6. Selecting rocks to comprise 1160# sample

The calculations shown below are done to aid in the field examination of the riprap sample. The inspector determines it is necessary to use a 1160 lb. sample. A sample can be fabricated that represents the specified gradation. The inspector selects "key" rocks for each of the points in the gradation. (see Figure 7-5) The rocks may be selected with the aid of a bathroom scale, spring scale, kitchen scale, or the perimeter measurement method above. These are the only rocks which are weighed or measured. After these six rocks are laid out, the inspector can "eyeball" the rocks between these "key" rocks. The calculations show that 497 rocks are needed between the 0.1 and 0.6 lb. range. This is too numerous to count. Using a weight of approximately 100# per cubic foot, the 174# sample is also 1.74 cubic feet or 13 gallons. Use a bucket to measure 13 gallons of this size rock. The next size range is 0.6# to 2.5# rocks. The 0.6 lb. "key" rock should be included in the count of 112 rocks needed. The rocks should be uniformly spread between the two key rocks. Avoid a cluster of rocks that are all the same size/weight. Next, for the 2.5-20 lb. range, the inspector selects 20 rocks that appear to be between the two "key" rocks in size. The 2.5-lb. "key" rock is the 21st rock. Next, for the 20 to 82 lbs. range, the inspector selects 6 rocks that appear to be between the two key rocks in size. The 20 lbs. "key rock" is the seventh rock. Only two rocks are needed that are 82 lbs. or larger. The 82 lb. "key rock" and the 116 lb. "key rock" are the two rocks. Figure 7-6 shows the rocks selected and laid out. Next, the inspector can lay the rock together in a measured area to see how the rock should look when placed on site.

This method is used to help an inspector visualize the specified gradation. The rock selected should be checked mathematically to be sure that the count was done correctly.

2 rocks x 99#	=	198#
8 rocks x 51#	=	408#
21 rocks x 11.25#	=	236#
112 rocks x 1.55 lbs.	=	173.6#
1.74 cu. ft. x 100#/cu.ft.	=	174 #
TOTAL		1189.6#

This is within 5% of the needed 1160 lbs. so OK.

C. Installation Tips

1. The rock gradation and filter gradation should be prepared before placement begins. Preparing the gradation as it is placed is not acceptable. It is too likely that the placed rock will be skip graded in spots.

2. Fill placed under rock protection should be compacted to a density equal to or greater than the existing in-place bank materials.

3. When placing rock under water, deposit it from a clam shell or bucket as close to the final location as possible.

4. In flowing water, when placing rock underwater, place the bedding only a short distance ahead of the rock. Check that the bedding is in the correct location just ahead of the placement of the rock.

5. Riprap placed on a bank can be encouraged to be smooth and to have smaller rocks fill the voids if the operator carefully places the flat portion of the bucket against the placed rock. Care should be taken to minimize rock breakage when this is done. Some rearranging can also be done with the teeth of a backhoe bucket.

6. The riprap should be installed beginning at the downstream end, working upstream. The rock should be placed beginning at the toe and working up the slope.

Table 7-2. Quick Field Guide for Sizing

P1+P2 (feet)	Weight (W) (lbs.)	d (inches)
14.4	1000	24
10.8	420	18
9.0	245	15
7.2	125	12
6.6	95	11
6.0	70	10
5.4	55	9
4.8	37	8
4.2	25	7
3.6	16	6
3.0	9	5
2.4	5	4
1.8	2	3

Table 7-3. Inches Expressed as Fraction of a Foot

1" = 0.08 feet	7" = 0.58 feet
2" = 0.17 feet	8" = 0.67 feet
3" = 0.25 feet	9" = 0.75 feet
4" = 0.33 feet	10" = 0.83 feet
5" = 0.42 feet	11" = 0.92 feet
6" = 0.60 feet	

Conversion Factor: 1 cubic foot = 7.4805 gallons
Therefore, a 5 gallon bucket has a volume of 0.6684 cubic feet, or about 2/3 cubic foot.

DERIVATION OF FIGURE 7-3.

This procedure uses a rock that is assumed to be an average between a perfect sphere and a perfect cube. These are blended to produce the formulas for developing Figure 7-3.

Perfect Sphere	Perfect Cube
Circumference: πd	Circumference: $4d$
$(P1+P2) = 2(\pi d) = 6.28d$	$(P1+P2) = 2(4d) = 8d$

Averaging these two values,

$(P1+P2) = (6.28d + 8d) = 7.14d$

(P1+P2) and d are both in feet. However, more frequently, d is used in inches. So the factor of 12 is included to use (P1+P2) in feet and d in inches.

$(P1+P2)/7.14 = d \times 12$ inches/foot

or

$d = 1.68 \times (P1 + P2)$

Perfect Sphere	Perfect Cube
Volume of sphere $= \pi d^3/6$	Volume of cube $= d^3$
$(P1+P2) = 2\pi d$	$(P1+P2) = 8d$
$d = (P1+P2)/2\pi$	$V = ((P1+P2)/8)^3$
$V = \frac{\pi (P1+P2)^3}{6 \quad (2\pi)^3} = \frac{(P1+P2)^3}{48\pi^2}$	$V = \frac{(P1+P2)^3}{512}$

$$V = \frac{(P1 + P2)^3}{473.74}$$

Specific gravity = 2.65

Density = 62.4 lbs/ft^3 x 2.65 = 165.4 lbs./ft^3

Weight = volume x density

$W = \frac{(P1+P2)^3}{473.74} \times 165.4$ lbs/ft^3	$W = \frac{(P1+P2)^3}{512} \times 165.4$ lbs./ft^3
$W = 0.349\ (P1+P2)^3$	$W = 0.323\ (P1+P2)^3$

Averaging these two conditions, as rock is rarely a sphere and never a cube,

$$W = 0.336\ (P1+P2)^3$$

This is close enough to 1/3 that 1/3 is used to simpify the calculations when this has to be done without a calculator. $W = 0.333\ (P1+P2)^3$

APPENDIX A.

BLANK DESIGN FORMS

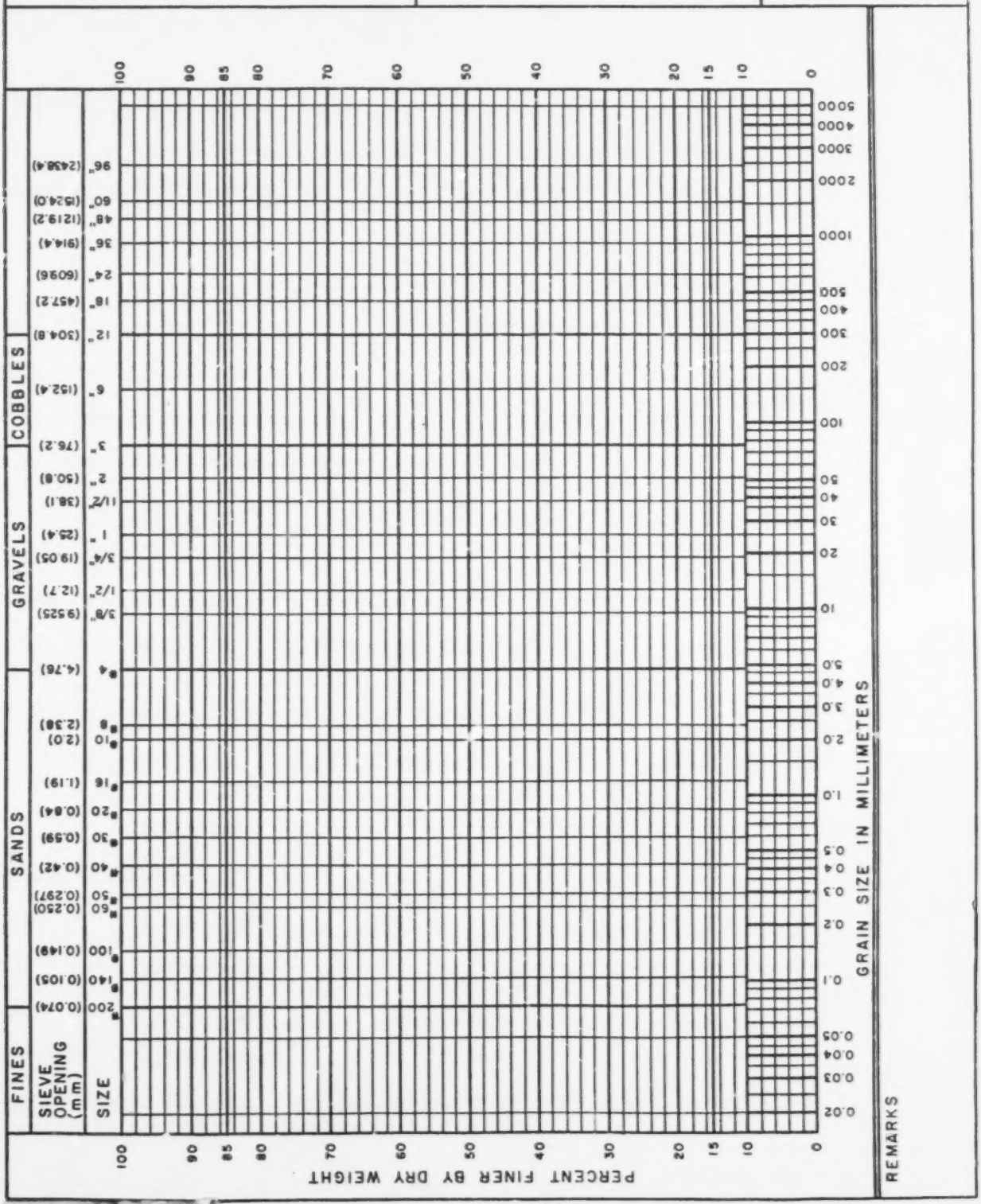
DESIGN CHARTS

NN-ENG-80
12-76
(FILE CODE ENG-13)

U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE	RIPRAP, FILTER OR BEDDING MATERIALS

PROJECT and STATE

DESIGNED AT	BY	DATE



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A

DESIGN FORM A
SCOUR PROTECTION FOR INLETS
MINNESOTA

Project_____County _____

By_____Date_____Ck'd By_____ Date_____

Description of Situation:

Pipe Diameter (do)_____ Peak Discharge (Q) _____

Median soil particle size (D50s)_____(in feet)_____

Pipe diameter to 3/2 power ($do^{3/2}$)_____

Radius of scour hole predicted by equation 3-1:

$$R = \left(0.15do + \frac{0.04Q}{(do)^{3/2}}\right)\left(\frac{do}{D50s}\right)^{1/5} =$$

Depth of Scour hole (S) by Equation 3-2:

$$S = \left(\frac{0.05Q}{(do)^{3/2}}\right) - D50s - 0.075(do) =$$

Mean stone diameter of riprap (D50) from equation 3-3:

$$D50 = \left(\frac{0.05Q}{(do)^{3/2}}\right) - 0.075(do) =$$

1.3 x D50 =

Riprap Gradation:

	(Table 2-2)	(Using D50)	(Using D50 x 1.3)
D100 =	1.5-2.0 D50		
D85 =	1.3-1.8 D50		
D50 =	1.0-1.5 D50		
D15 =	0.3-0.5 D50		

Note: The riprap within one pipe diameter of the inlet is to be the larger gradation where the median rock is (1.3 x D50).

DESIGN FORM A (Sheet 2 of 2)
SCOUR PROTECTION FOR INLETS

Filter/Bedding Requirements:

Thickness of Riprap: (see Chapter 2, Section E)

$1.25 \times D100_{MAX}$ = _____ (minimum of 9-12 inches)

Placing underwater? Yes No Ice or wave attack? Yes No

Add 6-12" to the thickness if subject to ice or wave attack.
Increase thickness by 50% if placing in water greater than 3' deep.

C

DESIGN FORM C
PIPE OUTLET PROTECTION
MINNESOTA TR-3

Reference: Section C in Chapter 3 of MN TR-3

Project: _____ County_____

By_____Date_____Ck'd By_____ Date _____

Pipe diameter (do) _____ Peak discharge (Q) _____

Tailwater (TW) _____ Soil median particle size (D50s)_____ - _____ ft.

$$D50 = \frac{C}{TW}\left(\frac{Q}{do}\right)^{4/3} \qquad \text{(Eq'n 3-4a)}$$

D50 - _____

Check Alternative Used:

☐ Alternative #1: Horizontal Blanket C=0.020 (see Figure 3-1)

For TW ≥ 0.5do, L1 - 3(do) $(Q/(do)^{5/2})$ (Eq'n 3-5) -

For TW < 0.5do, L2 - 1.8do $(Q/(do)^{5/2})$ + 7do (Eq'n 3-6) -

☐ Alternative #2: Preformed Scour Hole (see Figure 3-2)

S - $(0.05Q/(do)^{3/2})$ - D50s - 0.075do (Eq'n 3-2) S-_____

Select S - _____(must be ≥ S calculated here)

for S - 0.5 do C - 0.0125 (Eq'n 3-7a)

for S ≥ do C - 0.0082 (Eq'n 3-7b)

☐ Alternative #3: Lined Channel Expansion (Figure 3-3) C=0.016

Riprap Gradation:

D100 1.5-2.0 x D50

D85 1.3-1.8 x D50

D50 1.0-1.5 x D50

D15 0.3-0.5 x D50

Thickness of Riprap Layer: (see Chapter 2, Section E of MN TR-3)

1.25 x $D100_{MAX}$ - _____(minimum of 12 inches)

Filter/Bedding Requirements:

D

DESIGN FORM D
CHANNEL PROTECTION UPSTREAM FROM A STRUCTURE
MINNESOTA TR-3

Reference: MN-TR-3, Chapter 4, Section A

Project:_____County_____

By_____Date_____Ck'd By _____ Date_____

Velocity (V) _____ Flow Depth (d) _____

Height of Water over Weir (H)_____

A. (Eq'n 4-2) $D50 = 0.012\ V^3 / (d^{0.5}) =$ _____

B. D50 must be greater than or equal to 6 inches

Use the larger D50 of those calculated in A and B above = _____

Length of Protection (L1) = 2 x H = _____ (Eq'n 4-1)

Riprap Gradation: (from Table 2-2)

D100 1.5 - 2.0 x D50

D85 1.3 - 1.8 x D50

D50 1.0 - 1.5 x D50

D15 0.3 - 0.5 x D50

Thickness of the Riprap Layer: 1.25 x $D100_{MAX}$ _____

(See Chapter 2, Section E--minimum is 9-12 inch thickness)

Filter/Bedding Requirements:

E

DESIGN FORM E
OUTLET CHANNEL PROTECTION
FOR STRUCTURES AND ENERGY DISSIPATORS
MINNESOTA TR-3
Sheet 1 of 2

Reference: Minnesota Technical Release 3, Chapter 4, Section B

Project _____ County _____

By _____ Date _____ Ck'd By _____ Date _____

Structure Width (Sw) _____ Design Discharge (Q) _____

Elevation of Design discharge in channel (El) _____

Velocity (V) _____ Depth in channel related to V (d) _____

A. Eq'n 4-2: $D50 = 0.0012\ V^3/(d)^{0.5}$ = _____

B. Use form to design channel lining and calculate D50 _____

C. Use the larger of the D50 values calculated in A and B above

D50 = _____

D. Length of Protection (L1):

L1 = 1.5 x Sw = _____

L1 must not be less than 25 feet; Riprap must be placed to elevation El or higher.

Riprap Gradation: (from Table 2-2)

D100 1.5 - 2.0 x D50

D85 1.3 - 1.8 x D50

D50 1.0 - 1.5 x D50

D15 0.3 - 0.5 x D50

Thickness of Riprap = 1.25 x D100(max) = _____

Bedding and Filter: Use Soil Mechanics Note #1 and Chapter 2 of MN TR-3.

DESIGN FORM F
CHANNEL LINING
MINNESOTA TECHNICAL RELEASE NO. 3
Sheet 1 of 2

Reference: Minnesota Technical Release 3, Chapter 5

Project _____ County _____

By _____ Date _____ Ck'd By_____ Date_____

Design Discharge (Q) _____ Channel Bed Slope _____

Side Slope Ratio _____

☐ Triangular X-section ☐ Trapezoidal X-section

D50 selected: (sheet 2 of 2 for computations) _____

Riprap Gradation: (from Table 2-2)

D100 1.5 - 2.0 x D50

D85 1.3 - 1.8 x D50

D50 1.0 - 1.5 x D50

D15 0.3 - 0.5 x D50

Thickness of Riprap Layer: 1.25 x $D100_{MAX}$ = _____

(See Chapter 2, Section E--minimum thickness is 12 inches)

Bedding/Filter Design:

Design Sketch:

Design Form F for Channel Lining Riprap
Sheet 2 of 2

Design Q = Channel Slope =

D50 guess	n value	b, bottom width	d, flow depth	z, side slope	b/d	P/R	D50	n value
1	2	3	4	5	6	7	8	9

Trapezoidal Channel:

$A = bd + zd^2$
$P = b + 2d\sqrt{1+z^2}$
$R = A/P$

Triangular Channel:

$A = zd^2$
$P = 2d\sqrt{1+z^2}$
$R = A/P$

Manning's Equation:

$V = (1.486/n)R^{2/3}S^{1/2}$
Continuity Equation
$Q = VA$

1. Select an initial D50 size to try.
2. Use Figure 5-2 to estimate an initial n value.
3. Determine bottom width and depth for this n value using Manning's equation, the design discharge, and the channel bed slope.
4. Select a side slope ratio, z.
5. Calculate b/d and record in column 6.
6. Use Figure 5-3 to determine P/R from b/d. Record in column 7.
7. Use Figure 5-4 or 5-5 to determine the D50 rock size.
8. Use Figure 5-2 to affirm that the n value is close to what was assumed.
9. If the n value is not approximately the same as what was assumed, repeat the procedure with different values.

DESIGN FORM G
STREAMBANK PROTECTION
MINNESOTA TECHNICAL RELEASE NO. 3

Reference: Minnesota Technical Release No. 3, Chapter 6 and NNTC DN #4

Project _____ County _____

By _____ Date _____ Ck'd By _____ Date _____

1. Side Slope Ratio (z) _____ Cross-sectional Area (A) _____

Sketch of cross-section:

2. Perimeter (p) _____ feet Hydraulic Radius (r) _____ feet

3. Energy Slope (Se) _____

4. Reference Tractive Stress: $T_r = gw\ r\ s_e = 62.4\ \#/ft^2$ x _____ x _____ =

_____ psf (eq'n 6-5)

5. Bottom width (b) _____ feet Depth of flow (d) _____ b/d _____

6. C_{Ts} (Figure 6-1) _____ Max. Side Stress ($Ts = T_r \times C_{Ts}$) _____ psf

7. C_{Tb} (Figure 6-2) _____ Max. Bottom Stress ($Tb = T_r \times C_{Tb}$) _____ psf

ROCK SIZE TO TRY: _____

8. Mannning's n: (Eq'n 6-3 or 6-4) _____

$n = d^{1/6} / (21.6 \log (d/D50) + 14)$ or $n = .0395\ D50^{1/6}$

9. Angle of Repose ( )_____ $K = (1 - ((\sin^2 (\cot^{-1} z))/\sin^2 \Theta))^{1/2}$ _____

10. Factor of Safety (FS)(use 1.0 initially) _____

11. Allowable Tractive Stress = Tsa = K x 4.0 x D50 /FS = _____

In a straight reach compare the value in step 11 to the larger of the two values from steps 6 and 7. The allowable tractive stress must be greater than the maximum stresses on the sides and bottom. Otherwise, choose a larger riprap and repeat the design analysis. If Tsa is much greater than the maximum stresses, you may wish to try a smaller rock size. Continue with step 12 for riprap on a curve.

Actual Safety Factor: Tsa/(Tb or Ts, whichever is larger) = _____

12. Radius of Curve (r_c) _____ feet Top Width (w) _____ feet

w/r_c = _____

13. (Figure 6-3) Tc/T = _____ Maximum stress in curve Tc = T_r x Tc/T _____

In a curved reach, compare the value at the end of line 13 with those in lines 6 and 7. Line 13 must be larger or an error is likely. Then compare line 13 to line 11. The value in line 11 must be larger or a different size riprap should be chosen. The design procedure must be repeated.

Actual Safety Factor: Tsa/Tc = _____

14. Distance upstream of Pc to protect: Lu = 0.4 w = 0.4 x _____

(Eq'n 1-2) Lu = _____ feet

15. Distance downstream of Pt to protect (eq'n 1-3) = .4635 $r^{1/6}$ d / n =

.4635 x _____ x _____ / _____ = _____ feet

16. Avg. Velocity _____ ft/sec g = 32.2 ft/sec^2

17. (Eq'n 1-1) z = 1.5 $\{(Va^2w)/gr_c\}$ = _____ feet

Increase the riprap protection elevation by this amount, z, to account for superelevation of the flow due to the curve.

18. Toe Protection: Method A ____ or Method B ____

19. Riprap Gradation:

D100 1.5 - 2.0 x D50

D85 1.3 - 1.8 x D50

D50 1.0 - 1.5 x D50

D15 0.3 - 0.5 x D50

20. Thickness of Riprap Layer: 1.25 x $D100_{Max}$ = _____

minimum thickness is 12 inches

Filter/Bedding:

DESIGN FORM H
RIPRAP FOR FLOW IN CHANNEL BENDS
MINNESOTA TECHNICAL RELEASE NO. 3

Reference: Minnesota Technical Release No. 3, Chapter 1, Section E

Project _____ County _____

By _____ Date _____ Ck'd By _____ Date _____

Top Width (w) _____ feet Avg. Velocity (Va) _____ ft/sec

$g = 32.2$ ft/sec^2 Radius of Bend (r_c) _____ feet

(Eq'n 1-1) $z = 1.5\ ((Va^2 w)/gr_c) =$ _____ feet

Increase riprap protection elevation by this amount, z, to account for superelevation due to the bend.

Hydraulic radius (r) _____ feet Flow Depth (d) _____ feet

Manning's n _____

EXTENT OF RIPRAP: (Reference MN TR-3, Chapter 1)

See Figure 1-6 for layout. Compute upstream and downstream distances below.

(Eq'n 1-2) $Lu = 0.4\ w = 0.4 \times$ _____ = _____ feet

(Eq'n 1-3) $Ld = (0.4635\ r^{0.1667} d)/n =$ _____ = _____ feet

Design Sketch: (or attach drawing)

APPENDIX B. GLOSSARY

Angle of Repose - The angle of slope formed by particulate material under the critical equilibrium condition of incipient sliding. The angle at which the material rests if allowed to stand for a long period of time.

Apparent Opening Size - A measure of the largest effective opening in a filter fabric or geotextile (sometimes referred to as engineering fabrics), as measured by the size of a glass bead where five percent or less by weight will pass through the fabric (formerly called equivalent opening size, EOS)

Channel Shear Stress - The average shear stress occurring in a channel section for a given set of hydraulic conditions.

Composite Lining - Combination of lining materials in a given cross-section (i.e., riprap low-flow channel and vegetated upper banks)

Depth of Flow - The perpendicular distance from the bed of a channel to the water surface.

Design Discharge - Discharge at a specific location defined by an appropriate return period to be used for design purposes.

Filter - One or more layers of material placed below riprap to prevent soil piping and permit natural drainage.

Filter, Granular - A filter consisting of one or more layers of well graded granular material.

Flexible Lining - A channel lining material having the capacity to adjust to settlement; typically constructed of a porous material that allows infiltration and exfiltration.

Flow, Critical - Flow conditions at which the discharge is a maximum for a given specific energy, or at which the specific energy is minimum for a given discharge.

Flow, Gradually Varied - Flow in which the velocity or depth changes gradually along the length of the channel.

Flow, Nonuniform - Flow in which the velocity vector is not constant along every streamline.

Flow, Rapidly Varied - Flow in which the velocity or depth change rapidly along the length of the channel.

Flow, Steady - Flow in which the velocity is constant in magnitude or direction with respect to time.

Flow, Subcritical - Flow conditions below critical; usually defined as flow conditions having a Froude Number less than one.

Flow, Supercritical - Flow conditions above critical; usually defined as flow conditions having a Froude Number greater than one.

Flow, Uniform - Flow in which the velocity vector is constant along every streamline. The flow condition where the rate of head loss due to friction is equal to the bed slope of the channel.

Flow, Unsteady - Flow in which velocity changes in magnitude and direction with respect to time.

Flow, Varied - Flow in which velocity or depth change along the length of the channel.

Freeboard - Vertical distance from the top of the channel to the water surface at the design condition.

Gabion - Rectangular wire baskets filled with rocks used in the construction of a variety of erosion control structures. Also the name used for a number of these structures.

Geomorphology - The study of the characteristics, origin, and development of land forms.

Geotextile - A filter consisting of one or more layers of permeable textile. Also referred to as filter fabrics and engineering fabrics.

Hydraulic Radius - Flow area divided by the wetter perimeter. (A/P)

Hydraulic Resistance - Resistance encountered by water as it moves through a channel, commonly described by a roughness coefficient such as Manning's n.

Incipient Motion - The condition that exists just prior to the movement of a particle within a flow field. Under this condition, any increase in any of the factors responsible for particle movement will cause motion.

Mean Velocity - In hydraulics, the discharge divided by the cross sectional area of the flowing water.

Meander - One curved portion of a sinuous or winding stream channel, consisting of two consecutive loops, one turning clockwise and the other counterclockwise.

Median Diameter - The midpoint in the size distribution of sediment such that half the weight of the material is composed of particles larger than the median diameter and half is composed of particles smaller than the median diameter.

Normal Depth - The depth of a uniform channel flow.

Permeability - The property of a material or substance which describes the degree to which the material is penetrable by liquids or gases. Also, the measure of this property.

Permissible Shear Stress - Shear stress at which the channel lining will fail.

Permissible Velocity - The velocity which will not cause serious erosion of the channel lining material.

Rigid Lining - A lining material with no capacity to adjust to settlement; these lining materials are usually constructed of non-porous material.

Reverse Flow - Flow in a direction oppposite to that which would be expected.

Revetment - A channel bank lining designed to prevent or halt bank erosion.

Revetment Toe - The lower terminus of a revetment blanket where it intersects with the channel bottom; the base or foundation of a revetment.

Riprap - A well graded mass of durable stone, or other material that is specifically designed to provide protection from flow induced erosion.

Riprap, Placed - Consists of riprap set into place to form a well graded mass of material to provide protection from flow induced erosion. The placement is frequently done by equipment such as a crane and skip, dragline, or backhoe bucket.

Riprap, Grouted - Consists of riprap with all or part of the interstices filled with portland cement mortar to form a rigid lining.

Riprap, Wire-Enclosed - Consists of wire baskets filled with stone, connected together and anchored to the channel bottom or sides.

Rock Windrow - An erosion control technique that consists of burying or piling a sufficient suply of erosion-resistant material below or on the existing land surface along the bank, then permitting the area between the natural riverbank and the rock to erode until the erosion reaches and undercuts the supply of rock.

Rubble - Broken fragments of rock or debris resulting from the decay or destruction of a building.

Shear Stress - The force developed on the wetted area of the channel that acts in the direction of the flow, usually measured as a force per unit wetted area.

Side Slope - Slope of the sides of a channel; usually referred to by giving the horizontal distance followed by the vertical distance. For example, 3 to 1, or 3:1, meaning a horizontal distance of 3 feet to a 1 foot vertical distance.

Sieve Diameter - The size of the sieve opening through which the given particle will just pass.

Soil Piping - The process by which soil particles are washed in or through pore spaces in filters.

Standing Waves - Curved symmetrically shaped waves on the water surface and on the channel bottom that are virtually stationary.

Superelevation - Local increases in water surface on tne outside of a bend.

Thalweg - Line following the deepest part of a streambed or channel.

Uniform Flow - see Flow, Uniform

Velocity - A measure of the speed of a moving substance or particle given in feet per second.

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